

JAMES CLERK MAXWELL

MAXWELL: THINKING THE INVISIBLE

James Clerk Maxwell and the Art of Reasoning
Beyond What Could Be Seen

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In tribute to the 150th anniversary, in 2014, of Maxwell's presentation of
A Dynamical Theory of the Electromagnetic Field to the Royal Society in 1864.
The paper was formally published in 1865.

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Preface

We know about electrons and atomic structure. We know that radio waves, visible light, infrared radiation and X-rays belong to the same electromagnetic family. We know that the classical concepts of space and time would eventually be transformed by relativity.

Those things lay beyond Maxwell's scientific horizon.

Other ideas that now seem equally familiar occupied a very different position for him. That light was an electromagnetic disturbance was not inherited knowledge but a conclusion he helped construct. That gases should be understood as immense populations of moving molecules was still a contested physical picture, and the use of probability to describe their collective behaviour was itself part of the developing science.

For Maxwell, some of what we now call established physics was still hypothesis, inference or unfinished theory.

That difference creates one of the greatest difficulties in understanding him.

A modern student can encounter Maxwell's equations in a few pages of a textbook. Electricity and magnetism have already been unified. The electromagnetic field is already part of the language. The speed of light is already waiting inside the equations. Historical uncertainties have disappeared. Rival theories have been removed. Notation has been modernised. Arguments developed across decades have been compressed into a clean logical sequence.

The result is extraordinarily powerful physics, but it is a poor place from which to understand discovery.

The destination has become so familiar that the journey can look almost inevitable.

It was not.

This book begins by trying to remove that inevitability.

Its subject is James Clerk Maxwell, but its deeper concern is a problem that extends beyond any individual scientist:

How can we learn something real about a part of nature that we cannot directly see?

Nineteenth-century physics confronted this problem repeatedly.

Electricity could be produced, measured and transmitted, but its physical nature remained disputed. Magnetic effects could be mapped and manipulated, while the mechanism behind them was uncertain. Light could be reflected, refracted, polarised and made to interfere, but the nature of the medium through which it supposedly travelled remained unresolved.

The behaviour of gases could be measured with great precision, although no physicist could follow the trajectories of their individual molecules. The internal structure responsible for human colour perception could not be directly inspected. Even the constitution of Saturn's rings had to be inferred from astronomical observation and mechanics rather than touched, sampled or examined.

These were not empty problems waiting for a genius to fill them with the correct answer. They were crowded with competing possibilities.

The physics of the nineteenth century contained mechanical ethers, actions at a distance, electrical particles, lines of force, elastic media, molecular hypotheses and mathematical analogies. Scientists frequently agreed about experimental results while disagreeing profoundly about what those results meant.

Maxwell worked inside this contested landscape.

The familiar story says that he unified electricity and magnetism, discovered that light is electromagnetic and gave physics the equations that now bear his name.

All of that requires qualification.

The equations most readers know today are not simply the equations Maxwell wrote in their modern form. His electromagnetic theory developed through several different mathematical and physical representations. Some of the mechanical imagery he used was explicitly provisional. Some predictions worked impressively. Others did not. Parts of his theory were reinterpreted, simplified or rejected by scientists who came after him.

Even the Maxwell we now encounter in textbooks is partly a creation of later generations.

That history matters, but this book asks another question before reaching the familiar outcome.

What did Maxwell actually have in front of him at each stage? What had already been measured? What theories were available? Which of them did he demonstrably know? What did his equations represent at that moment? What changed from one paper to the next? What did he keep when a physical model changed? What did he abandon? And what did other scientists, confronted with related evidence, do differently?

Those last questions are important because this is not intended to be a biography in which exceptional genius is assumed on page one and confirmed on every subsequent page.

Maxwell may prove distinctive. Or he may prove to be one particularly powerful participant in a wider culture of mathematical analogy, mechanical modelling and indirect inference in the nineteenth century. Different parts of his science may even reveal different ways of reasoning.

That possibility must remain open.

A biography that cannot discover that its central interpretation is wrong is not really investigating its subject. It is illustrating a conclusion chosen in advance.

There is another temptation this book will resist.

Scientific creativity is often described through moments of revelation. Newton sees an apple fall. A scientist dreams of a solution. Another steps away from a difficult problem and suddenly understands it.

Such stories are attractive because they compress years of thought into a scene that can be remembered. They also blur several very different things.

An observation is not a theory.

An intuition is not a demonstration.

A model is not necessarily a claim about reality.

A mathematical result is not automatically a physical interpretation.

And a successful physical interpretation is not yet experimental confirmation.

With Maxwell, the distinction is especially important.

The surviving evidence does not give us unrestricted access to his private thought. Finished scientific papers usually present an argument in the order in which it can be justified to readers, not necessarily in the order in which it occurred to the author. Later recollections may reveal how a scientist came to describe a discovery after the event without providing a transparent record of the original mental process.

For that reason, this book will not attempt to narrate undocumented episodes inside Maxwell's mind.

Where interpretation goes beyond the surviving record, it will be identified as interpretation rather than presented as documented fact.

The book will follow something we can examine more securely:

the changing representations he left behind.

A fluid analogy appears. Then a mechanical structure. Then a different mathematical formulation. Certain relations are preserved. Some mechanisms disappear. Measurements constrain what remains possible. A problem encountered in one domain may later appear again in another, although that recurrence must not be mistaken in advance for proof of a unified method.

This documentary trail does not give us Maxwell's consciousness. It gives us something historically more reliable: evidence of scientific work changing form.

And that may be enough to ask a more precise question about creativity.

Perhaps the interesting feature of Maxwell's science was not an unusual supply of mysterious intuitions. Perhaps it lay partly in the way he negotiated a difficult boundary: using physical mechanisms strongly enough to make

them productive, while sometimes withholding commitment to their literal truth; allowing mathematical relations to survive when the picture that helped generate them no longer commanded the same confidence.

That is only a working proposition.

It has to survive comparison.

William Thomson also used mechanical representation and analogy. W. J. M. Rankine developed sophisticated hypothetical mechanisms while thinking explicitly about different kinds of physical theory. Gustav Kirchhoff, Hermann von Helmholtz, Wilhelm Weber, Rudolf Clausius and others confronted related questions from different directions.

Their presence is essential.

Without them, Maxwell would be compared only with the future, and the future makes an unfair opponent.

Faraday is more important still.

Michael Faraday and Maxwell approached physical problems with very different intellectual resources. Faraday's experimental Diary preserves unusually rich traces of scientific work in progress. Maxwell's mathematical papers and correspondence preserve a different kind of record.

The relationship between them is therefore not simply the familiar story of an experimental genius followed by a mathematical genius.

Faraday's ideas about induction, dielectric action, magnetism, light and lines of force contained physical commitments of their own. Maxwell did not merely translate them into equations. He selected, transformed and extended them.

At moments he made aspects of Faraday's world mathematically visible.

At others, the mathematics changed the world being represented.

That exchange lies near the centre of this book.

But Maxwell's electromagnetic work cannot be understood in isolation.

While developing ideas about electricity and magnetism, he was also studying colour, molecular motion, measurement and stability.

That simultaneity matters.

The Maxwell who constructed mechanical models of an electromagnetic medium was also the Maxwell who had begun treating enormous populations of invisible molecules statistically. The physicist trying to infer mechanisms of colour vision from matching experiments was working during the same broad period in which he was thinking about structures that could not be directly observed in electricity and magnetism.

The young mathematician who investigated the stability of Saturn's rings confronted another version of a recurring scientific problem: when direct inspection is impossible, what can mathematical constraint tell us about what a system can and cannot be?

These parallels may reveal a unity in Maxwell's scientific practice.

They may not.

The chronology will be laid out before that interpretation is offered.

The story will therefore move forward largely in the order in which Maxwell encountered his problems rather than separating his life into retrospective categories such as "the electromagnetic Maxwell", "the statistical Maxwell" and "the Maxwell of colour".

Those Maxwells were one person. Their problems overlapped in time. Their possible connections should be allowed to emerge rather than manufactured after the fact.

The book will also continue after Maxwell's death.

He died in 1879, at the age of 48, before experimental electromagnetic waves had transformed the reception of his theory and long before the technological world shaped by the electrodynamics of the nineteenth century acquired its form in the twentieth century.

After his death, other scientists began reconstructing him.

His theory was rewritten. Its notation changed. Mechanical pictures lost authority. Certain quantities were pushed into the background. Some later returned. A complex mathematical theory eventually became the compact set of equations now printed in textbooks.

Einstein inherited not simply Maxwell's original theory but versions of Maxwell already transformed by Hertz, Lorentz and others.

Looking at this afterlife allows us to distinguish at least two different historical questions:

What did Maxwell actually construct?

And what did later physics decide that Maxwell had constructed?

They are not always the same question.

That difference is one reason a historical Maxwell remains interesting even when the physics is already known.

The purpose of this book is therefore not to make Maxwell more prophetic.

It is almost the opposite.

The more carefully we remove the knowledge of the future, the more remarkable some of his decisions become, while others become less mysterious.

We encounter a scientist surrounded not by ignorance but by competing knowledge. We see measurements with substantial uncertainties rather than textbook constants. We see theories before their notation became familiar, models before history selected which parts would survive, mistakes and unresolved problems.

And we see places where Maxwell himself knew that his theory had reached a difficulty rather than pretending that later physics was already contained inside it.

This is the Maxwell I want to understand.

Not the marble figure standing at the beginning of modern physics.

Not merely the name attached to four equations.

And not a visionary who somehow possessed knowledge of discoveries that had not yet happened.

A working physicist trying to establish what could legitimately be inferred from an incomplete and contested physical world.

If we can recover that world with enough discipline, another question may become possible.

Not:

How did Maxwell see the future?

But:

How did Maxwell decide what physics could legitimately infer when the underlying mechanism remained hidden, disputed or perhaps not there to be found at all?

That is where this book begins.

Prologue

The Number Before the Theory Was Safe

On 19 October 1861, James Clerk Maxwell wrote to Michael Faraday.

He had been working on electricity and magnetism.

The paper in which the work would appear was not yet complete.

Its machinery was elaborate.

Space was filled with an electromagnetic medium. Magnetic action was represented through rotating cells. Electrical processes would soon require still more machinery. The mechanism was hypothetical. In Part II, published earlier in 1861, Maxwell had already described the idle-wheel connexion as provisional and temporary.

Yet the mathematics had produced something he thought could test it.

He told Faraday:

“The conception I have hit on has led, when worked out mathematically to some very interesting results, capable of testing my theory...”

The phrase is worth stopping over.

Capable of testing my theory.

Not proving it.

Not revealing the final constitution of nature.

Testing it.

An electrical number

Maxwell had used the electrical measurements of Wilhelm Weber and Rudolf Kohlrausch.

They had determined a relation between different systems of electrical measure.

The quantity had the dimensions of a velocity.

It was not a measurement of light.

It came from electricity.

Maxwell connected that electrical quantity with the mechanical properties of his proposed electromagnetic medium.

Then he made an additional assumption.

He told Faraday that, having calculated the elasticity of the electromagnetic medium in air, he was:

| “assuming that it is the same with the luminiferous ether”.

Under that assumption, he calculated the velocity of transverse vibrations.

The result was:

193,088 miles per second.

Another number

Maxwell then placed beside it a value he attributed to Fizeau’s direct measurement of the velocity of light:

193,118 miles per second.

The difference was tiny.

About thirty miles per second in more than 193,000.

As Maxwell had the figures before him, the match was extraordinary.

He wrote:

| “This coincidence is not merely numerical.”

It is tempting to make this the moment when Maxwell suddenly discovered that light was electromagnetic.

The documents do not require such a scene.

They show something more precise.

An assumption had already entered the calculation.

A numerical comparison then strengthened Maxwell's confidence in it.

The formula came first

The next part of the letter supplies an unusually valuable piece of contemporaneous evidence.

Maxwell told Faraday:

“I worked out the formulae in the country, before seeing Weber's number...”

By Maxwell's own report, the formulae preceded Weber's number.

The letter then records the sequence more fully: the formulae were worked out in the country; Weber's number was consulted; the elasticity was determined from it; Maxwell assumed the same elasticity for the luminiferous ether; the wave velocity followed; and only then came the optical comparison.

That is enough to make the comparison a genuine test in one important sense.

It does not tell us everything Maxwell already knew about the approximate scale of electrical velocities.

It does not tell us whether he knew every relevant earlier result.

It does not reconstruct a private moment of surprise.

But it does establish an order of documented acts:

formulae,

Weber's number,

elasticity,

assumption of the same elasticity for the luminiferous ether,

wave velocity,

optical comparison.

The theory and the relation

Then Maxwell added the sentence that will matter throughout this book.

He thought there was now:

“strong reason to believe, whether my theory is a fact or not, that the luminiferous and the electromagnetic medium are one.”

The qualification is remarkable.

Whether my theory is a fact or not.

A result produced inside a theory might deserve confidence even while the literal status of the entire theory remained unsettled.

That does not mean Maxwell was indifferent to mechanism.

He was constructing one in extraordinary detail.

It means that different parts of the construction could carry different evidential weights.

But the numbers were not as clean as they looked

There is another reason not to turn the letter into a legend.

The optical value Maxwell quoted to Faraday was not the number Fizeau had actually published.

Historical reconstruction indicates that Maxwell had found 193,118 miles per second in a handbook by J. A. Galbraith and Samuel Haughton, where the value was attributed to Fizeau.

Fizeau's published result was different.

When Maxwell published Part III of *On Physical Lines of Force* in January 1862, he used another optical value again.

There the electrical and optical velocities differed by roughly 1.3 percent.

The near-perfect match of the private letter had already disappeared.

Maxwell still drew the inference.

The evidence would move again

By 1865, Léon Foucault's improved optical measurement was available.

Its value was farther from Maxwell's electromagnetic number than the Fizeau value Maxwell had printed in 1862.

Maxwell included that less favourable number himself.

The theory survived.

Then, in 1868, Maxwell, with Charles Hockin carrying out the galvanometer and shunt comparisons, measured the relation between electrical units again.

Their result moved the electrical value substantially, to about 288,000,000 metres per second, below every optical estimate Maxwell had printed.

The theory survived that too.

The celebrated numerical coincidence was therefore never one fixed fact standing outside history.

Its values changed.

Its evidential context changed.

Its interpretation changed.

Why begin here?

Because the episode contains the central difficulty of Maxwell's science in miniature.

Something cannot be directly seen.

A representation is built.

The representation contains assumptions.

Mathematics exposes a relation.

Measurement constrains it.

A comparison supports part of the construction.

But success does not tell us automatically which part of the representation should be believed literally.

That problem recurs throughout Maxwell's work.

Hidden strain

Years earlier, Maxwell had studied patterns produced when transparent solids were stressed.

The internal state of the material could not simply be inspected.

Its consequences could.

Colour

He would infer properties of human vision from controlled colour matches.

The physiological machinery itself remained largely hidden.

Saturn

He would determine what Saturn's rings could not be made of by asking which proposed constitutions were dynamically unstable.

No voyage to Saturn was required.

Molecules

He would describe populations of molecules no observer could follow individually.

Probability would replace exhaustive trajectories.

Electromagnetism

And in the work that made him famous, he would fill apparently empty space with increasingly sophisticated representations, then later set aside much of the detailed machinery in the 1865 paper while retaining relations the machinery had helped disclose.

A dangerous word: genius

Maxwell is often called a genius.

The word explains almost nothing.

If it means that he produced unusually consequential scientific work, it is harmless.

If it means that insight arrived by a private faculty inaccessible to historical reconstruction, it becomes an excuse not to examine what he actually did.

This book takes the opposite route.

It follows dated representations.

What information was available?

What did Maxwell demonstrably know?

What did he write?

What changed between one representation and the next?

What survived?

What failed?

We know the ending

That creates our main disadvantage.

We know that electromagnetic waves exist.

We know that the mechanical ether did not survive.

We know that kinetic theory became central to statistical physics.

We know that Saturn's rings consist primarily of enormous numbers of separate particles.

We know about electrons, relativity and quantum mechanics.

Maxwell did not.

The future cannot be used as evidence available to him.

Not an empty black box

The unknown world of nineteenth-century physics was also not empty.

Where later physics would place fields, electrons or statistical ensembles, Maxwell and his contemporaries already had competing contents.

Faraday's lines of force.

Weber's interacting electrical particles.

Elastic-solid ethers.

Rankine's molecular vortices.

Clausius's molecules.

Mechanical analogies of many kinds.

The problem was not merely that the inside was unseen.

There were too many plausible ways to fill it.

What counts as evidence?

That is why mechanism alone could not decide.

A hidden model had to earn its scientific role through consequences.

It might reproduce known laws.

Predict a new relation.

Survive a perturbation test.

Explain an experimental regularity.

Or fail.

Failure matters throughout this book because it tells us which parts of a representation did not survive independent constraints.

Maxwell's wrong results will not be removed from the story to make the right ones look inevitable.

A question the book can fail to answer

There is a second danger.

After reading enough Maxwell, almost any recurring feature can begin to look uniquely Maxwellian.

So this book will not merely collect examples of his use of analogy, models or provisional mechanisms.

His contemporaries used them too.

William Thomson did.

William Rankine did.

Others separated description from mechanism even more sharply.

The comparative question is therefore open from the beginning:

Did Maxwell use provisional representations in a meaningfully distinctive way, or are we seeing a broader nineteenth-century scientific practice magnified by studying one man closely?

The answer may be the second, because the test is deliberately allowed to fail. This book will treat the candidate pattern as weakened or defeated if Maxwell's methods differ fundamentally from one domain to another, if the same practices are equally characteristic of his contemporaries, if his relation to experiment changes radically between subjects, or if the supposed unity appears only after later historians reorganise his work.

Those conditions are stated here before the cases are judged so that the conclusion cannot choose its test after seeing the outcome.

The first document already warns us

The October 1861 letter does not give a philosophy of science.

But it gives us a useful constraint.

Maxwell could write, in one letter, that a mathematical result was capable of testing his theory and that the resulting physical inference might remain important "whether my theory is a fact or not".

The distinction is there in his own words.

The rest of the book asks how often that distinction reappears, how much work it does, and whether Maxwell's contemporaries handled the same problem differently.

No Eureka required

We do not need to know the exact instant at which Maxwell "realised" the electromagnetic nature of light.

We do not need to imagine him staring at a number in astonishment.

The documentary sequence is already richer than such a story.

He formed a conception.

He worked out the formulae.

He consulted Weber's number.

He determined the elasticity from it.

He assumed the same elasticity for the luminiferous ether.

He obtained the wave velocity.

He compared the result with an optical value.

He told Faraday that the result could test the theory.

Then the numbers changed.

And the theory changed.

The relationship survived.

That is where our story begins.

Chapter I

The Boy from Glenlair

There were things.

Doors, locks and keys. Streams whose course disappeared from sight. Bell wires passing into parts of a house a child could not see.

And there was a boy who wanted to know what happened next.

James Clerk Maxwell was born in Edinburgh on 13 June 1831, the son of John Clerk Maxwell and Frances Cay. He was their only child to survive infancy. His earliest years were spent largely at Glenlair, the family estate in Galloway in southwest Scotland, where his father was developing the house and managing the property.

For once, we do not have to begin with a memory written after Maxwell became famous.

In April 1834, when James was not yet three, his mother wrote to her sister Jane Cay about the child's persistent curiosity. She described his preoccupation with doors, locks and keys, his investigation of streams and hidden bell wires, and a question that, she wrote, was "never out of his mouth":

| "Show me how it does."

The spelling belongs to the family record. The curiosity belongs to the child.

This is unusually valuable evidence because it is contemporaneous. Frances Maxwell was not remembering the childhood of a celebrated physicist. She was describing her young son.

What the letter documents is simple but striking. Maxwell wanted to know how things operated, including things whose connecting mechanism disappeared from view.

It does not tell us why.

It certainly does not tell us that field theory was somehow latent in the nursery.

That connection would be ours, not his.

The responsible observation is narrower: curiosity about hidden connection appears very early in the documentary record.

A world of mechanisms

Glenlair gave such curiosity abundant material.

John Clerk Maxwell had trained as an advocate, although his interests ranged well beyond law. He was strongly attracted to practical mechanics, machines and improvement, and he took an active role in the development of the estate.

The environment in which James grew up therefore contained both natural processes and constructed mechanisms.

For the biographer, there is a temptation to turn this into a developmental theory: repeated exposure to mechanisms formed a habit that later became scientific method.

The surviving evidence does not allow that conclusion.

What can be said is that the objects mentioned in the 1834 letter belonged to Maxwell's immediate physical environment.

The child encountered effects whose causes were partly hidden.

He asked about them.

For the moment, that is enough.

Loss

His early childhood was interrupted by the illness and death of his mother.

Frances Maxwell died in 1839, when James was eight.

She had taken an active role in his early education. During her illness, a tutor was employed. The arrangement failed. The surviving account says that the tutor was rough with the boy, who was reported as slow at learning, and that the experiment was eventually pronounced unsuccessful.

After his mother's death, Maxwell's upbringing involved several members of the family.

Jane Cay, his mother's sister, remained an important figure and maintained a close relationship with him. But when Maxwell later attended school in Edinburgh, his principal home there was 31 Heriot Row, the house of his father's sister Isabella Wedderburn. Jane Cay provided care at intervals rather than serving as his sole substitute mother.

These details may seem minor.

They are not.

The mythology of childhood often simplifies a network of people into one emotionally satisfying story. Our task is to preserve the network.

The same restraint applies to the death of Maxwell's mother.

It would be easy to construct a psychological narrative in which early bereavement produced inwardness, independence or a lifelong desire to find order beneath uncertainty.

There is no adequate evidence for such a causal claim.

The loss belongs in the story because it belonged in Maxwell's life.

It does not become an explanation for his later physics.

Edinburgh Academy

In November 1841, aged ten, Maxwell began attending the Edinburgh Academy.

The transition was difficult.

His appearance marked him out immediately. Campbell's later account describes the homespun clothes, unusual shoes and rural manner that attracted the attention of other pupils.

Unlike the 1834 letter, this evidence is retrospective.

Campbell was writing decades later, after Maxwell's death, and the distinction matters.

His narrative nevertheless records an awkward entry into school life. Maxwell was mocked. The nickname that remained attached to him there was "Dafty."

Later sources sometimes spell it "Daftie", but Campbell and Garnett give "Dafty".

The same account adds a useful detail: Maxwell apparently made little effort to get rid of the nickname.

That complicates the simplest picture of a passive victim.

There are accounts of rough treatment and teasing. Rev. W. Macfarlane, a former schoolmate, later recalled Maxwell eventually turning forcefully on those who tormented him and then gradually winning the respect even of the most thoughtless of his schoolfellows.

It is reasonable to say that Maxwell was mocked and at times roughly treated.

It would be less responsible to build a modern psychological diagnosis of sustained bullying from a narrow set of retrospective sources.

More importantly, the story does not remain one of exclusion.

Maxwell formed durable friendships.

Lewis Campbell became a lifelong friend and eventually his biographer. Peter Guthrie Tait became another close companion and later an important mathematical physicist.

Maxwell also began to succeed within the school.

The boy initially regarded as rustic and eccentric acquired respect. He performed strongly in several subjects, won prizes and developed an increasingly visible mathematical ability.

The isolated genius is therefore the wrong picture.

Maxwell was unusual, and he was mocked.

But he also became embedded in a social and intellectual network that lasted for decades.

Saturdays with his father

The surviving record becomes more concrete when Maxwell's father was in Edinburgh.

Campbell recalled that father and son spent Saturday half holidays together. They visited places including Leith Fort, the works associated with the Granton railway and the geological exposures at Salisbury Crags.

On Saturday, 12 February 1842, Maxwell was given what Campbell called a special treat: he was taken to see electro-magnetic machines.

The detail is genuine.

Its later significance must not be exaggerated.

Nothing in the record shows that Maxwell, then ten, saw those machines and recognised the subject that would later dominate his scientific reputation.

The episode is valuable for a different reason.

Electromagnetism entered his observable world long before it entered his mature theory.

At this stage it was apparatus.

Something that could be demonstrated.

Something that did things.

There is no reason to add destiny to the scene.

From looking to representing

During his school years Maxwell's interest in geometry became increasingly serious.

One problem involved the construction of oval curves by means of pins, string and geometrical constraints.

The starting point was concrete.

A curve could be drawn.

But Maxwell generalised the construction.

Instead of treating an oval as one isolated shape, he studied a family of curves generated by relationships among several foci.

At fourteen, the work attracted the attention of James David Forbes, professor of natural philosophy at Edinburgh University.

The paper, On the Description of Oval Curves, and Those Having a Plurality of Foci, was communicated to the Royal Society of Edinburgh by Forbes in April 1846, with remarks by Forbes appended.

The achievement was remarkable.

It was not creation from nothing.

Related curves had been studied previously, including by Descartes. Maxwell's work nevertheless extended and generalised the construction.

The episode gives us an unusually early lesson in what scientific originality actually looks like.

A problem already has a history.

A young investigator enters it.

Something changes.

The contribution lies in that change.

Object and relation

The geometrical episode introduces a distinction that will remain useful.

The pieces of string and the pins are physical objects.

The oval drawn between them is another object.

But the mathematical content does not reside in any one piece of string or any one curve.

It resides in a relation.

Change the particular construction while preserving the relation and the mathematics survives.

This is not yet evidence of a mature Maxwellian philosophy of models.

It would be anachronistic to make it one.

But it is evidence that Maxwell was already working with a transformation fundamental to mathematical science:

from a particular object to the relation that generates it.

That operation expands what can be understood.

The visible shape is no longer the end of observation.

It becomes evidence of a rule.

The problem with “genius”

At this point a biographer is almost expected to use the word.

Genius.

Maxwell’s mathematical ability was plainly exceptional.

But “genius” becomes dangerous when it stops being a description and begins functioning as an explanation.

Why did he solve the problem?

Because he was a genius.

Why did he notice the connection?

Because he was a genius.

Why did other capable scientists take different routes?

Because Maxwell was a genius.

Nothing has actually been explained.

This book will therefore use the word sparingly.

If Maxwell’s scientific style proves distinctive, the difference should be visible in what he did and in comparison with what others did under similar conditions.

The label should come after the evidence, not replace it.

Light enters the story

Sometime in 1847, near the end of Maxwell's school years, another important episode occurred.

With his uncle John Cay, Maxwell visited the Edinburgh instrument maker William Nicol and saw experiments involving polarised light and the colours displayed by unannealed glass.

Maxwell subsequently pursued the phenomena himself. The surviving accounts describe a simple polariscope, pieces of unannealed glass that he prepared, coloured drawings of the observed patterns and the sending of some of those drawings to Nicol. Nicol later gave Maxwell a pair of prisms of his own manufacture.

The episode has unusually tangible features.

It involves an instrument, observations, drawings and subsequent experimental work.

Light had entered Maxwell's science.

Not yet as an object whose nature he was trying to explain.

At first, light was doing something else.

It was revealing an optical consequence of a physical condition that ordinary vision could not detect.

That distinction will become important.

The child of the 1834 letter had asked about streams and bell wires whose course disappeared from sight.

Thirteen years later, the scientific problem was becoming more disciplined.

The question was no longer merely where something hidden went.

It was how an inaccessible physical condition could leave an observable trace.

And that leads from biography into experiment.

Chapter 2

Geometry, Glass and Invisible Strain

A transparent piece of glass can conceal a mechanical history.

Seen in ordinary light, it may appear uniform. Yet cooling or applied force can leave the material in a state of internal strain.

Now examine it with polarised light.

Patterns emerge.

Colours appear where none were previously visible.

The stress has not become an object that the eye can inspect directly. What has become observable is an optical consequence of the mechanical state.

That distinction is fundamental to experimental science.

An instrument rarely makes the invisible visible in a simple sense.

More often, it establishes a relation between something inaccessible and something that can be detected.

Maxwell encountered this problem before he was twenty.

Edinburgh University

Maxwell entered the University of Edinburgh in 1847, aged sixteen.

His geometrical work continued, but experiment became increasingly important.

The later image of Maxwell as an almost purely mathematical theorist can obscure this side of his scientific life.

He constructed apparatus.

He observed.

He measured.

He compared theoretical consequences with experiment.

And, from an early stage, experimental disagreement mattered.

His encounter with polarised light is a good place to see this beginning.

Nicol and polarised light

As Chapter 1 described, Maxwell's 1847 visit to William Nicol introduced him directly to experiments with polarised light and unannealed glass.

He then continued experimenting with the phenomena himself, in experiments where optical effects revealed a hidden mechanical condition.

The episode is not a story of isolated invention.

Nicol supplied instrumentation and practical optical knowledge.

David Brewster had already investigated optical effects produced by stressed or unannealed transparent materials.

The subject had a scientific history before Maxwell entered it.

What matters is the role it soon played in his own work.

A hidden state, an observable consequence

Mechanical strain inside a transparent material cannot ordinarily be mapped by looking at the material.

Polarised light changes the experimental situation.

Stress can alter the optical behaviour of the solid. When appropriately polarised light passes through it and is analysed, the resulting pattern depends on the material's mechanical condition.

We can describe the logic in modern language as:

mechanical state , optical consequence , observed pattern

The words are ours.

The experiment was nineteenth century.

To turn the pattern into physics, however, observation alone was insufficient.

A mathematical theory had to connect mechanical deformation with the optical effect.

That is where Maxwell's interests in geometry, mechanics and experiment met.

When theory disagrees

Maxwell's paper *On the Equilibrium of Elastic Solids* was read to the Royal Society of Edinburgh on 18 February 1850.

Its opening is worth taking seriously because it begins not with theoretical triumph but with failure.

Maxwell wrote:

“There are few parts of mechanics in which theory has differed more from experiment than in the theory of elastic solids.”

The problem concerned theories derived from apparently plausible assumptions about the constitution of matter and molecular forces.

The mathematics had produced consequences.

Experiment had refused to obey them.

Maxwell discussed the inadequacy of earlier molecular theories of elasticity and the importance of formulations capable of accommodating the experimentally observed behaviour more successfully.

This is an excellent early case for our purposes because it prevents an easy story about theory.

A mathematically coherent model can begin from physically plausible assumptions and still fail.

The failure does not tell the scientist automatically what is wrong.

It says only that some part of the chain from assumptions to measurement requires reconsideration.

Prediction and optical test

Niven's editorial preface (1890) to Maxwell's 1850 work establishes the direction of the optical reasoning clearly enough for our purposes.

Maxwell developed theoretical deductions concerning elastic solids and then described experiments intended to test consequences of the theory in optics.

The important sequence is therefore:

mechanical theory , predicted optical consequence , experimental comparison

We should not reverse that sequence without direct evidence.

This is important because it changes the lesson.

The polarised light does not simply disclose an unknown stress distribution to Maxwell.

Instead, it provides an experimentally observable consequence against which a mechanical theory can be tested.

The hidden mechanical state and the visible optical effect are connected through theory.

A modern comparison: the inverse problem

There is a related concept that will recur later in this book.

Modern science often speaks of an inverse problem.

In a forward problem, a model and its parameters are specified and the observable consequences are calculated.

In an inverse problem, observations are used to infer the underlying state or parameters that could have produced them.

The term is much later than Maxwell and should not be attributed to him.

Nor should his 1850 paper be presented as though it were organised explicitly around the modern inverse problem. The evidence presently supports the forward direction more securely: theoretical deductions followed by experimental optical tests.

But the modern distinction is still useful for understanding a broader family of scientific situations.

Sometimes physics predicts an observation from a model.

Sometimes it tries to infer hidden structure from an observation.

Often the two directions interact.

What matters historically is to establish which direction Maxwell was actually using in each case.

What the instrument contributes

The polariscope did more than improve eyesight.

It changed the accessible evidence.

Without the optical arrangement, different regions of a strained transparent solid might look alike.

With polarised light, their mechanical differences could produce distinct optical consequences.

The instrument therefore altered what could become an experimental fact.

But this fact was not theory free.

The colours and bands did not arrive labelled “stress”.

Their interpretation depended on optics and mechanics.

Scientific observation was already layered:

material state,

interaction with light,

instrument,

visible pattern,

mathematical interpretation.

This becomes increasingly important as physics moves toward objects and processes that cannot be inspected directly.

A later name: photoelasticity

Today we would naturally place this work within the history of photoelasticity, the use of optical effects to investigate mechanical stress.

The term and the mature experimental discipline came later.

Using the modern word can help orient the reader, but it should not make the historical practice look more settled than it was.

Maxwell was entering an evolving field of elasticity, optics and experimental mechanics.

Brewster had established important optical phenomena.

Stokes had developed important theoretical work on elasticity.

Nicol provided optical expertise and instrumentation.

Maxwell brought these resources together in his own work.

Again, originality was distributed across a network.

Models and constraints

The opening of Maxwell's paper is particularly revealing because the theories that failed were not absurd.

They rested on plausible ideas about microscopic matter.

That is precisely what makes the failure scientifically valuable.

If a theory constructed from a particular molecular hypothesis produces the wrong relation among measurable elastic quantities, experiment can constrain the hypothesis even when the molecules themselves cannot be inspected.

The scientist does not need direct visual access to the proposed mechanism in order to rule out consequences of that mechanism.

This distinction will become important in several later episodes.

Dynamical stability will constrain possible constitutions of Saturn's rings.

Measurements of gas behaviour will constrain models of invisible molecular motion.

Electrical and magnetic measurements will constrain competing accounts of electrodynamic action.

Colour matching will constrain theories of visual response.

The examples are different, and the book will not assume in advance that Maxwell used one identical method in all of them.

But they share an epistemic circumstance:

the mechanism is not directly available, while consequences are.

Theory is not simply first, experiment second

The usual diagram of scientific work is linear:

theory,

prediction,

experiment,

confirmation or rejection.

Maxwell's early work already shows why this is too simple.

Experimental facts had already helped produce the theoretical problem.

The failure of older elasticity theories motivated the search for a better formulation.

Optical experiments provided another mode of testing.

Mathematical analysis determined which consequences should follow.

Observed effects then bore on the adequacy of the analysis.

Theory and experiment altered each other's possibilities.

That interaction matters more than deciding which came "first".

A representation is not the thing represented

The coloured patterns in strained material are not themselves the mechanical stress.

They are effects that stand in a physically interpretable relationship to it.

The equation is not the stress either.

It is another representation.

The physical system, the mathematical description and the optical signal are therefore distinct.

Yet science works precisely because relations can be established among them.

This distinction will later become much harder.

When Maxwell begins using fluids, vortices and mechanical structures to represent electromagnetic relations, we will have to ask repeatedly:

What belongs to the physical phenomenon?

What belongs to the model?

What belongs to the mathematics?

And what evidence allows one to move from one level to another?

The glass experiments provide an early, relatively concrete case.

Failure can be productive

A failed physical model need not be useless.

It may expose which quantities matter.

It may identify a relation that experiment can test.

It may reveal exactly where an assumption breaks down.

And it may be possible to preserve part of the mathematical structure while abandoning the original microscopic picture.

This possibility will become central later.

But we should not assign it to Maxwell as a distinctive philosophy yet.

Rankine, Thomson, Stokes and other contemporaries were also confronting the relation between hypothetical mechanisms and mathematical description.

Some developed elaborate mechanical pictures.

Some emphasised experimentally constrained relations.

Some did both.

The comparison has not yet been made.

Light before the electromagnetic theory of light

There is a historical contrast worth preserving.

Light was already part of Maxwell's experimental life years before it entered his electromagnetic theory.

At Edinburgh, light functioned as an investigative tool.

Its polarisation helped test predictions concerning the mechanical condition of matter.

Later, light would enter Maxwell's theory from another direction, through electricity, magnetism and the dynamics of a medium.

Maxwell in 1850 did not know what he would conclude in the 1860s.

The two episodes belong together only because history eventually placed them in the same life.

Our task is to preserve the interval between them.

The boundary

When Maxwell left Edinburgh for Cambridge in 1850, several elements of his scientific practice were already visible.

He had moved from geometrical constructions to more general mathematical relations.

He had worked with instruments.

He had tested theoretical consequences experimentally.

He had encountered a case in which plausible microscopic assumptions failed against measured behaviour.

And he had used polarised light to connect an otherwise inaccessible mechanical state with observable optical effects.

That does not yet establish a unified Maxwellian method.

It establishes something more modest.

Maxwell had already worked repeatedly near a boundary between:

what could be observed, what could be represented, and what could legitimately be inferred.

Cambridge would place that boundary inside a much larger intellectual world.

Faraday was developing a physical conception of lines of force.

Ampère had built a powerful electrodynamics around forces between currents.

Weber had already formulated electrical action through moving charged particles.

William Thomson was using mathematical analogies to connect apparently different branches of physics.

Rankine would work simultaneously with elaborate hypothetical mechanisms and explicit distinctions between different forms of physical theory.

There was no single road toward a theory of electromagnetism.

There were competing physical pictures, mathematical techniques and standards of explanation.

Before Maxwell's own route can be understood, those alternatives have to be taken seriously.

That is where the comparison begins.

Chapter 3

Cambridge, Analogy and the Physics Maxwell Inherited

When Maxwell arrived at Cambridge in October 1850, electricity and magnetism were not waiting to be unified.

They were already crowded with theories.

There were laws that worked, experiments that could be repeated, mathematical techniques of formidable power and physical pictures that disagreed about what electricity and magnetism actually were.

This is easy to forget because modern textbooks introduce the subject after much of the disagreement has disappeared.

For Maxwell, the disagreement was the subject.

Before asking what he eventually contributed, we need to reconstruct the intellectual landscape he entered.

Cambridge

Maxwell first entered Peterhouse and soon moved to Trinity College.

Cambridge offered something Edinburgh had not: immersion in one of the strongest mathematical cultures in Britain.

The Mathematical Tripos rewarded speed, technique and the ability to solve difficult problems under pressure. Students preparing for it often worked with private tutors known as coaches, whose training could be extraordinarily demanding.

Maxwell studied under William Hopkins, one of the most celebrated of them.

He graduated in 1854 as Second Wrangler and was bracketed first for the Smith's Prize with Edward Routh.

These distinctions established him as an exceptionally capable Cambridge mathematician.

But technical virtuosity was not the same thing as choosing a scientific problem.

Shortly before graduating, Maxwell began looking seriously toward electricity.

A letter to William Thomson dated 20 February 1854 preserves this stage unusually well. Maxwell asked how a reader with a popular acquaintance with electrical demonstrations should proceed into the deeper literature. In particular, he wanted to know how Ampère and Faraday should be arranged, and when Thomson's own papers ought to be read.

What matters here is the structure of the request.

Maxwell was asking for an intellectual map.

He did not write as someone already possessing the answer.

And the names he chose reveal the difficulty, because Ampère and Faraday did not offer two versions of the same theory.

They represented strikingly different ways of organising the electrical world.

Ampère: force without a visible intermediary

André-Marie Ampère had built one of the great mathematical achievements of early electrodynamics.

Following Ørsted's discovery that electric currents affect magnetic needles, Ampère developed a quantitative theory of forces between current carrying circuits.

Its success was remarkable.

But its physical architecture was very different from the one later associated with Maxwell.

The mathematics described interactions between electrical currents across space. What happened in the intervening region did not need to carry the explanatory burden in the way Faraday later demanded.

For a modern reader, accustomed to fields, this can feel incomplete.

Historically, it was not obviously incomplete at all.

Newtonian gravitation had made mathematical action between separated bodies enormously successful, even though the metaphysical status of action at a distance remained controversial.

Electrodynamics could therefore pursue a comparable ambition: determine the law connecting sources and forces and calculate the observable result.

A precise law might be scientifically powerful even when no directly observable intermediary occupied the space between interacting bodies.

There was another possible way to think.

Faraday: the space between matters

Michael Faraday approached the same physical world differently.

He had little of the advanced mathematical education that structured Cambridge physics.

His scientific power came instead from experimental practice, physical representation and an extraordinary ability to create new experimental situations.

The space surrounding magnets, wires and charged bodies mattered to him.

He represented magnetic and electric action through lines of force.

These were not initially equations.

They arose from experimental and geometrical ways of thinking about the direction and distribution of physical action.

Iron filings around a magnet could display patterns.

A magnetic needle could explore directions point by point.

Electromagnetic induction showed that changing electrical or magnetic conditions could produce effects elsewhere.

Faraday increasingly treated the intervening region not as an irrelevant void across which a force simply acted, but as physically involved in the phenomenon.

This was more than a diagrammatic convenience.

It was a different way of distributing the explanatory burden.

Ampère's mathematics could ask:

What force does this current element exert on another?

Faraday's programme increasingly encouraged another question:

What physical condition exists throughout the region between them?

That distinction is schematic, and neither scientist can be reduced to a sentence.

But it identifies a genuine choice confronting anyone entering electrodynamics in the 1850s.

Should theory concentrate primarily on relations among sources and forces?

Or should it attempt to represent a physical state distributed through space?

Maxwell would not simply select one option and reject the other.

His route would be more complicated.

William Thomson: analogy before Maxwell

A third figure is essential.

William Thomson, later Lord Kelvin, was only seven years older than Maxwell, yet by the time Maxwell sought his advice he had already developed influential methods for connecting different branches of mathematical physics.

In 1842 Thomson examined the mathematical correspondence between heat conduction and electrostatics.

The phenomena were physically different.

Heat flowing through a solid was not electricity distributed around charged bodies.

But the laws governing them could possess a partial mathematical similarity.

That similarity could make one science illuminate another.

Maxwell would later define a physical analogy as:

“that partial similarity between the laws of one science and those of another which makes each of them illustrate the other.”

This is more precise than saying that analogous phenomena must resemble one another physically.

They need not.

What corresponds can be the relations.

That gave analogy considerable scientific power.

A mathematical structure already understood in one field could become a tool for approaching another.

Thomson had demonstrated the usefulness of this method before Maxwell entered electromagnetism.

And he went further.

In June 1847 Thomson wrote to Faraday about a mathematical analogy involving an elastic solid. He explicitly warned that he had produced only a mathematical analogy and had not ventured to make it the basis of a physical theory. Yet he also suggested that a theory of this type might eventually account for magnetic effects and, in Thomson's words, “in all probability explain the effect of magnetism on polarized light”.

This matters greatly for our comparison.

Mechanical representation of electromagnetic relations did not begin with Maxwell.

Nor was caution about the ontological status of a mathematical representation uniquely Maxwellian.

Thomson already distinguished between mathematical analogy and physical theory.

The question is therefore not whether Maxwell later used analogies.

It is what he did with them.

Analogy as movement between sciences

The word analogy can sound weak today.

It may suggest metaphor.

In nineteenth-century mathematical physics it could be much more powerful.

An analogy could transfer mathematical organisation from a comparatively well understood domain into a poorly understood one.

Suppose the equations describing heat flow and an electrical problem have corresponding forms.

Then methods developed for one can illuminate the other.

The analogy may suggest useful variables.

It may reveal boundary conditions.

It may make a previously obscure relation calculable.

And it can do so without asserting that the two physical systems are made of the same things.

This creates an important freedom.

A scientist can borrow structure without necessarily borrowing mechanism.

But there is a corresponding danger.

A representation can become so vivid that its usefulness begins to look like evidence for its literal physical truth.

The boundary between analogy as instrument and analogy as ontology will become one of the central difficulties in Maxwell's electromagnetic work.

He was not alone in confronting it.

Rankine: two methods and two kinds of hypothesis

William John Macquorn Rankine provides an especially demanding comparison.

Like Thomson, he belonged to the Scottish world of mathematical and engineering physics.

He also worked with elaborate hypothetical mechanisms, including a theory involving molecular vortices in heat.

Yet in 1855 he explicitly distinguished two methods of forming physical theory.

He called them the hypothetical and abstractive methods.

The distinction was not simply between bad speculation and good mathematics.

Rankine's treatment was subtler.

Within hypothetical theory he distinguished what he called objective hypotheses, adopted as probable representations of states of things that might actually exist, from subjective hypotheses, employed as convenient means for expressing the laws of phenomena.

The difference is crucial.

A hypothetical mechanism could function scientifically without necessarily being asserted as literal reality.

Rankine went further still.

He argued that a hypothetical theory might be necessary as a preliminary step, bringing phenomena into sufficient simplicity and order before an abstractive theory could be constructed.

This makes him a particularly dangerous comparison for our working proposition.

It would be easy to say that Maxwell was distinctive because he used mechanical hypotheses productively without committing fully to their literal truth.

But Rankine was articulating closely related possibilities explicitly.

And he was doing so while pursuing hypothetical molecular mechanisms himself.

The comparison therefore cannot be won by vocabulary.

It has to be won, if at all, by practice.

What kinds of hypotheses did each man build?

How long did they retain them?

What relations did they extract?

What happened when a mechanism changed?

Those are historical questions.

The comparison becomes harder

Imagine describing Maxwell without these controls.

He uses analogies between different branches of physics.

That sounds distinctive.

Thomson had already done so.

He constructs mechanical representations while warning against literal interpretation.

Again, potentially distinctive.

But Thomson had already separated mathematical analogy from commitment to physical theory.

He uses hypothetical mechanisms while allowing that useful relations might outlast them.

Rankine had already developed an explicit vocabulary for closely related distinctions.

The comparative field therefore prevents easy praise.

That is its purpose.

If Maxwell does turn out to have a recognisable style, it has to emerge against competitors this strong.

Weber: another physical architecture

There was also a fundamentally different electromagnetic programme.

Wilhelm Weber had formulated an electrodynamic force law in 1846 built around interactions between electrical particles and their relative motion.

This was not a primitive theory waiting to be replaced by fields.

It was a sophisticated rival physical architecture with significant mathematical and explanatory ambitions.

Weber's programme demonstrates how differently the same experimental domain could be conceptualised.

One theory could place explanatory weight on forces among electrical particles.

Another could place it on states of an intervening medium.

Both could be mathematical.

Both could confront experiment.

The disagreement was not between mathematics and intuition.

It was between different mathematical pictures of physical reality.

This point will matter repeatedly.

Maxwell's theory did not emerge against a blank background.

It entered a competition among serious alternatives.

What did Maxwell actually know?

The distinction between what was available and what Maxwell demonstrably knew now becomes essential.

The 1854 letter gives direct evidence that Ampère, Faraday and Thomson were entering Maxwell's working horizon.

That is much stronger evidence than merely observing that their papers had been published.

The two categories must remain separate.

A scientific idea can exist in the literature without being part of a particular scientist's active intellectual world.

Availability is historical context.

Reading, citation, correspondence and discussion provide stronger evidence of awareness.

This distinction becomes especially important when researchers reach similar ideas independently.

Maxwell asks for a map

The structure of the 1854 letter is revealing.

Maxwell did not simply ask Thomson for facts.

He wanted an order.

How should these bodies of work be approached?

At what stage should one read one author rather than another?

That is a request for a map through incompatible representations.

Ampère's electrodynamics looked unlike Faraday's experimental researches.

Faraday's lines of force looked unlike Thomson's mathematical analogies.

Weber offered another framework again.

To enter electricity seriously meant learning how to move among these forms of description.

The problem was not only difficult physics.

It was translation.

Cambridge mathematics and Faraday's pictures

Maxwell's Cambridge training gave him formidable mathematical resources.

Faraday's work offered something that Cambridge technique did not automatically provide: a physical conception organised around lines, spatial distributions and local relations.

The familiar summary says that Maxwell mathematised Faraday.

That is true at such a high level of abstraction that it can become misleading.

Mathematics does not arrive and simply translate an intact physical picture.

Choosing a mathematical representation changes what can be expressed.

Some aspects of Faraday's physical thinking become clearer.

Others may disappear.

Still others may acquire consequences Faraday had never formulated.

The process transforms both the mathematics and the physical representation.

Maxwell would have to decide which aspects of Faraday's world could be represented through existing mathematics and which demanded new constructions.

This was not transcription.

It was theory building.

The first Maxwellian question

What, then, was distinctive about Maxwell at this point?

We do not yet know.

By 1854 he possessed exceptional mathematical training.

He had experience with geometry, experiment and physical representation.

He was entering a field populated by incompatible programmes.

He sought guidance from Thomson.

And he was increasingly drawn toward Faraday's work.

But nothing so far establishes a uniquely Maxwellian method.

Thomson already possessed a language of mathematical analogy.

Rankine could move between hypothetical machinery and abstraction.

Faraday had developed a sophisticated physical conception of the intervening medium.

Weber possessed a mathematically organised alternative ontology.

Ampère had demonstrated the power of exact electrodynamic laws.

If we stopped here, the honest conclusion would be that Maxwell entered a scientific culture already rich in many of the intellectual tools later associated with him.

That is exactly why what happens next matters.

What a useful analogy must not claim

Maxwell's first major electromagnetic paper would open by discussing physical analogy.

The problem he faced was subtle.

A purely formal mathematical translation might preserve equations while losing some of the physical intuition that made Faraday's work powerful.

A literal mechanical model might provide physical intelligibility while claiming more about unseen reality than the evidence allowed.

Between those possibilities lay a flexible methodological space already explored in different ways by Thomson and Rankine.

Maxwell would enter that space with his own construction.

Chapter 5 will therefore not ask whether he invented physical analogy.

He did not.

It will ask something narrower:

What happened when Maxwell used analogy to reconstruct Faraday's lines of force?

That question can be answered from a dated paper.

For the first time, we will be able to examine Maxwell's electromagnetic practice directly rather than infer it from biography.

The comparison begins there.

Chapter 4

Colour: Inferring the Eye from What It Sees

A beam of yellow light can look yellow.

A suitable mixture of red and green light can also look yellow.

To an observer, under the right conditions, the two may be indistinguishable.

Physically, however, they need not be the same light.

That distinction was not Maxwell's discovery.

Newton had already recognised a version of it in the *Opticks*. Colours produced by composition, he observed, could resemble homogeneous spectral colours in appearance while differing in the physical constitution of the light. Newton also represented mixtures geometrically through a colour circle and a centre of gravity construction.

More than a century later, Maxwell entered a problem that therefore already possessed both physical and geometrical histories.

His contribution would lie less in announcing that appearance and physical constitution could differ than in turning colour matching into a controlled quantitative experiment.

The hidden system he was probing was not an ether or a molecule.

It was the human visual system.

Two problems called colour

Colour seems at first to belong to light.

Sunlight passes through a prism and spreads into a spectrum. Different spectral components can be physically distinguished. A physicist might therefore imagine that a complete theory of colour should simply be a complete theory of light.

But that is only part of the problem.

Physically different stimuli can produce the same perceived colour, while changes in the observer can alter which stimuli appear equivalent.

Colour therefore belongs to a relation among physical stimulus, sensory system and perception.

That distinction had deep roots.

Newton had established that compound and homogeneous lights could coincide in colour appearance without becoming physically identical.

Thomas Young then proposed a physiological explanation of a different kind.

Young and three responses

In his Bakerian Lecture at the beginning of the nineteenth century, Young confronted a difficulty.

If the spectrum varied continuously, would the retina need a distinct resonant mechanism for every possible colour?

He suggested instead that the number of fundamental retinal responses might be small.

He proposed three principal sensitivities.

The precise assignment of colours evolved in his writings, but the conceptual step was decisive.

The enormous diversity of perceived colour might be generated from a limited number of physiological response channels.

Young supplied a physiological hypothesis.

He did not yet possess Maxwell's later quantitative programme of colour matching.

Pigments are not lights

Another difficulty came from a familiar observation.

Painters knew that blue and yellow pigments could make green.

It was tempting to expect blue and yellow light to behave similarly.

They do not.

The distinction is obvious once additive and subtractive mixing are taught separately.

Historically, establishing that separation required experiment.

Helmholtz addressed it explicitly in 1852, distinguishing the physical process involved when coloured lights are combined from the selective absorption occurring when pigments are mixed.

Maxwell subsequently discussed the same experimental history in his 1856 report *On the Theory of Compound Colours with reference to Mixtures of Blue and Yellow Light*. There he referred to experiments with rotating coloured sectors, including work by James David Forbes in Edinburgh in 1849.

The apparently simple question of blue plus yellow therefore forced a separation among three levels:

the spectral composition of light,

the behaviour of coloured materials,

and

the resulting visual sensation.

Grassmann before Maxwell

A second contemporary comparison is essential.

In 1853 Hermann Grassmann published mathematical laws of colour mixture.

Grassmann treated colour combination through a linear structure involving three independent variables.

This matters because a modern reconstruction could easily make Maxwell appear to have invented the three dimensional mathematical treatment of colour.

He did not.

The intellectual landscape already contained Young's physiological hypothesis, Newton's geometry of mixtures, Helmholtz's optical analysis and Grassmann's mathematical laws.

Whether Maxwell knew Grassmann's 1853 paper at the relevant stage must be established separately.

Availability is not awareness.

Until direct evidence of reading or citation is found, Grassmann belongs to the historical comparison class, not automatically to Maxwell's documented intellectual inputs.

This distinction is important because independent or partially independent development can itself be historically revealing.

The colour top

Maxwell attacked colour experimentally with a simple but powerful apparatus.

In *Experiments on Colour, as perceived by the Eye, with remarks on Colour-Blindness*, published in the mid 1850s, he used rotating discs divided into adjustable coloured sectors.

When the discs rotated rapidly enough, the separate sectors were no longer perceived individually.

The eye reported a mixture.

The proportions, however, remained measurable.

This transforms the problem.

Instead of merely saying that two colours look similar, an observer can specify the proportions of components required to produce a match.

The equality remains perceptual.

The conditions producing the equality become quantitative.

That is one of Maxwell's important steps.

A visual judgement acquires numerical coordinates.

Forbes before Maxwell

Forbes had already experimented with rotating colours in 1849, and Maxwell himself later acknowledged those experiments.

Again, originality emerges inside an existing practice.

Maxwell did not create the rotating colour experiment from nothing.

What he developed was a progressively more systematic quantitative programme.

Adjustable sectors allowed ratios to be measured.

Repeated matches could be compared.

Different observers could be tested.

Colour deficiency could become experimental evidence rather than simply a clinical curiosity.

Three numbers

Suppose three reference stimuli are chosen.

A target colour is then matched by adjusting their relative contributions.

If the match is possible, the target can be represented quantitatively.

A vast range of perceptual appearances can thereby be organised through three independent variables.

This does not mean Maxwell alone discovered the abstract fact that colour mixture can be represented in three dimensions. Grassmann had already formulated three dimensional linear laws, while Newton's colour circle provided an earlier geometrical ancestry.

Maxwell's distinctive contribution lay increasingly in connecting such structure to measured colour matches made by real observers.

The geometry became experimental.

What does a colour match establish?

This is where the epistemic problem becomes especially interesting.

Suppose two physically different spectra produce the same perceptual judgement.

What has been established?

Not that the lights are physically identical.

Newton had already warned against that conclusion.

What has been established is that, for the observer under those conditions, the visual system maps those different stimuli onto the same perceptual result.

That equality is empirical.

It can be reproduced.

It can be quantified.

It can be compared across observers.

And it places constraints on any plausible account of the visual mechanism.

The physiological machinery remains hidden.

The relations it produces do not.

Young returns as an experimental hypothesis

Young's three response proposal could now be subjected to a much stronger form of test.

If normal colour matching genuinely requires three independent variables, that is consistent with a visual system possessing three independent classes of initial response.

The experiment does not show those receptors.

It constrains models of them.

That distinction must remain sharp.

Maxwell did not inspect three cone types.

He measured relations among stimuli and perceptual matches.

The physiological hypothesis gained support because it could account for the dimensionality of those relations.

Colour blindness as a natural experiment

Colour deficient observers provided an even sharper test.

If normal vision behaves as though three independent response dimensions contribute to matching, altered visual systems should change the structure of possible matches.

Maxwell investigated colour blindness experimentally.

This transformed a variation among observers into evidence about the system generating colour perception.

A component of the mechanism remained inaccessible.

Its alteration could nevertheless change measurable relations.

That makes colour deficiency a natural experiment.

The logic is powerful:

alter the system,

observe which distinctions disappear,

infer constraints on the hidden organisation.

Again, the inference is not direct observation.

It is structured indirect evidence.

Katherine Maxwell

The observer mattered because colour matching ended in human perception.

Katherine Maxwell participated in this work.

The historical record explicitly notes observations made by Mrs Maxwell and Maxwell himself.

That is enough for the present chapter.

We do not need to claim more than the source establishes.

Her presence matters scientifically as well as biographically.

A second observer makes it possible to distinguish, at least in part, between a relation peculiar to Maxwell's own visual system and one reproduced in another person.

The observer was part of the apparatus.

From paper colours to spectral mixtures

Rotating coloured papers had limitations.

Pigments possess complicated reflection spectra.

A red paper is not a pure spectral red.

A green paper does not reflect only a single wavelength.

Maxwell therefore developed more controlled optical methods.

His colour box used slits, prisms and optical arrangements to combine selected spectral regions and compare mixtures quantitatively.

His major paper *On the Theory of Compound Colours, and the Relations of the Colours of the Spectrum* was received by the Royal Society on 5 January 1860, communicated by Stokes and read on 22 March.

The surviving manuscript and diagrams remain in the Royal Society archive.

The apparatus itself belongs to a broader surviving material history of Maxwell's experimental work.

The change in method mattered because spectral components were better physically defined than coloured papers.

The mapping between physical stimulus and perceptual equality could therefore be tested with much greater precision.

What Maxwell added to the existing landscape

By this point the comparison can be stated more carefully.

Newton had already distinguished similarity of colour appearance from identity of physical constitution and had represented mixtures geometrically.

Young had proposed a three component physiology.

Helmholtz had clarified the distinction between mixing lights and mixing pigments.

Grassmann had formulated linear laws of colour mixture in three dimensions.

Maxwell's contribution lay in bringing several strands into sustained quantitative experimental contact.

He measured colour matches.

He used adjustable proportions.

He moved from coloured papers toward spectral mixtures.

He compared observers.

He exploited colour deficiency.

And he used these measurements to test the physiological implications of trichromatic vision.

That is a narrower claim than making Maxwell the originator of three dimensional colour theory.

It is also stronger because it is historically defensible.

The Rumford Medal

In November 1860 Maxwell received the Royal Society's Rumford Medal for his work on colour.

The fact of the award is secure.

We do not need to embellish it with an unverified paraphrase of the Society's reasoning.

Recognition matters because it shows that the colour work was not an eccentric side project remembered only because Maxwell later became famous for electromagnetism.

His contemporaries already regarded it as important work.

But recognition should not be confused with completion.

The physiology remained only partially constrained.

A retrospective window: three cone classes

Here, and only here, we can deliberately allow later physiology into the chapter.

Modern human colour vision begins with three classes of cone photoreceptors whose spectral sensitivities overlap.

Their signals are subsequently transformed by retinal and neural circuitry, including opponent processes.

Direct measurements of cone photopigments and receptor spectral sensitivities became possible only much later, especially through physiological and microspectrophotometric work in the 1960s.

Those measurements supplied a biological layer of evidence unavailable to Maxwell.

The important historical point is not that Maxwell predicted the full architecture of modern colour vision.

He did not.

It is that psychophysical measurements had already placed strong quantitative constraints on the first stage of the system long before direct physiological access became possible.

The relations were measurable before the mechanism could be examined directly.

May 1861

The most famous episode in Maxwell's colour work occurred at the Royal Institution in May 1861.

Maxwell demonstrated the principle of reconstructing a colour appearance from three separately recorded components.

Thomas Sutton prepared photographic records of a coloured tartan ribbon through different filters.

The images were projected through corresponding coloured filters and superimposed.

A coloured image appeared.

The event is often called the first colour photograph.

That description needs qualification.

The underlying principle was important, but the photographic chemistry did not behave as a simple modern reconstruction suggests.

The available photographic emulsions were extremely insensitive to red light.

A straightforward red filtered exposure should therefore have produced very little useful record.

Later historical analysis, particularly Ralph Evans's discussion in 1961, showed that the successful result probably depended on shorter wavelength radiation, including ultraviolet reflected by parts of the dyes, contributing to the nominally red record.

The demonstration succeeded.

But part of the physical pathway was not the one the simplified legend implies.

When a successful experiment has the wrong reason inside it

This does not make the demonstration worthless.

It makes it scientifically more interesting.

The conceptual architecture was sound:

make separate records,

recombine the corresponding components,

exploit the properties of human colour vision.

But the specific photographic implementation included detector behaviour that complicated the intended causal chain.

An experiment can therefore succeed while containing an unintended mechanism.

That lesson extends far beyond photography.

Filters leak.

Detectors possess response curves.

Materials reflect radiation outside the visible spectrum.

Apparatus has physics of its own.

The result cannot be understood simply by reading the experimenter's intention.

One has to reconstruct what physically happened.

Perception and measurement

Colour also forces us to refine the word observation.

An observer looks through an instrument and reports a match.

That judgement is perceptual.

It is also experimentally constrained.

The proportions of the stimuli are controlled.

Repeated observations can be compared.

Different observers can be compared.

Colour deficient vision changes the structure of the matches.

Scientific objectivity here does not arise by eliminating the observer.

It arises by structuring the conditions under which the observer reports.

That is an important difference.

Map and mechanism

The empirical colour relations can remain useful even as physiological explanation becomes more detailed.

A colour match measured in the nineteenth century does not cease to be a match because twentieth-century neurophysiology discovers opponent circuits.

The empirical relation survives a change in the mechanism used to explain it.

That possibility is close to a theme we will later encounter in Maxwell's electromagnetic work.

But the comparison should not yet be promoted into a conclusion about Maxwell's unified method.

Newton, Young, Helmholtz and Grassmann already show that colour science was a collective problem of representation, measurement and mechanism.

The question is not whether Maxwell alone recognised this structure.

He did not.

The question is what he added to it.

Several scientific problems at once

The chronology matters.

Maxwell's colour work overlapped with his early electromagnetic work.

His 1855 colour investigations belong to the same period in which On Faraday's Lines of Force was taking shape.

His major quantitative colour paper appeared in 1860.

The Royal Institution demonstration followed in 1861.

During those years he was also developing kinetic theory and moving toward the mechanical electromagnetic constructions of On Physical Lines of Force.

Textbook categories separate these subjects.

Maxwell's working life did not.

That simultaneity does not prove a common method.

It merely gives us the evidence required to test whether one existed.

A juxtaposition, not yet a lineage

The colour experiments and the electromagnetic work can now be placed beside one another without claiming that one taught Maxwell how to do the other.

In colour, physically different stimuli can produce the same measured perceptual relation.

In electromagnetism, Maxwell will soon ask whether different physical representations can preserve the same mathematical relations.

The resemblance is ours to investigate.

It is not yet a documented transfer inside Maxwell's mind.

That distinction matters.

The next chapter therefore turns back in time slightly and follows a different thread that had already begun while the colour experiments were developing.

Faraday's lines of force.

Maxwell was about to ask what mathematics could preserve from a physical picture that was powerful, unconventional and difficult to express in the language of Cambridge analysis.

That is where his first major electromagnetic transformation begins.

Chapter 5

Faraday and Maxwell

Michael Faraday did not need equations to make empty space physically interesting.

That sentence should not be mistaken for saying that he rejected mathematics.

His experiments were quantitative, disciplined and extraordinarily sophisticated.

But the physical language in which he represented electrical and magnetic action differed sharply from the dominant mathematical treatment of forces acting between distant bodies.

Lines mattered.

The intervening region mattered.

Direction mattered.

For James Clerk Maxwell, this created an unusual problem.

How could one make Faraday's physical conception mathematically productive without replacing it with a theory Faraday had not given?

The physical world Maxwell inherited from Faraday

Faraday's electrical researches had already transformed the space between bodies from a passive gap into part of the phenomenon.

Electromagnetic induction depended on changing physical conditions.

Dielectrics affected electrostatic induction.

Magnetic and electrical actions could be represented through lines whose arrangement described the state of the region surrounding bodies.

Faraday did not supply Maxwell with the equations that later textbooks would call Maxwellian.

He supplied something more difficult to translate:
a physical way of organising phenomena.

Translation without replacement

Maxwell's 1855–56 paper *On Faraday's Lines of Force* announces the problem directly.

He wants to present Faraday's ideas in mathematical form.

But he is wary of two opposite dangers.

One is to begin from a mathematical formula and lose sight of the physical phenomena.

The other is to commit too strongly to a physical hypothesis and accidentally import features that have no evidential warrant.

His proposed tool is physical analogy.

A physical analogy uses a similarity of mathematical relations between different domains to illuminate one through the other.

The analogy can calculate without requiring literal identity.

The imaginary fluid

Maxwell's first major device is an incompressible fluid.

Lines of force are represented as if they were streamlines.

The velocity of the imagined fluid represents the intensity and direction of force.

The construction lets Maxwell transform a difficult geometry of electrical and magnetic action into relations familiar from hydrodynamics.

But he immediately controls its status.

The fluid is not offered as the substance of electricity.

It is not a claim about what fills space.

Maxwell states that it is:

“not even a hypothetical fluid which is introduced to explain actual phenomena”.

That sentence matters because it removes an easy retrospective mistake.

Maxwell is using detailed physical imagery.

He is simultaneously denying that the image is a literal physical theory.

A representation can calculate

The imaginary fluid therefore has an unusual status.

It is richer than bare notation.

One can picture its motion.

One can use equations developed for fluids.

But its scientific value does not depend on discovering that electricity literally consists of such a fluid.

The representation carries relations.

That distinction will return repeatedly.

Premature explanation

Maxwell also warns against forcing an explanation too early.

Near the end of the fluid discussion he contrasts the dangers of a premature theory claiming to explain causes with the possibility that a more mature theory may eventually provide physical explanation after nature has been more fully interrogated.

The important point is not that Maxwell opposes physical explanation.

He does not.

He postpones commitment when the evidence cannot yet support it.

That is a more demanding stance than either “models are merely fictions” or “mechanical pictures are reality”.

Faraday's electrotonic state

The paper then becomes more difficult.

Faraday had introduced an electrotonic state in his early work on electromagnetic induction.

Whatever physical condition the term represented was not directly measurable as an ordinary force acting at one instant.

Yet changes associated with it were connected with induced electrical effects.

Maxwell needed a mathematical representation capable of carrying that structure.

He introduced what he called:

“Electro-tonic functions, or components of the Electro-tonic intensity.”

These functions are ancestors of what later mathematics would treat through the vector potential.

But that later name should not be allowed to make the 1855 concept seem finished in advance.

Maxwell says what he does not know

The most revealing passage is a self-report.

Maxwell writes:

“The idea of the electro-tonic state, however, has not yet presented itself to my mind in such a form that its nature and properties may be clearly explained without reference to mere symbols.”

The limitation is his own.

He is not claiming that Faraday's theory is deficient because it lacks a satisfactory mechanical embodiment.

He is saying that he himself does not yet possess one.

That distinction matters.

The symbols can be used before the physical nature of the represented state has become clear.

Artificial notation

Maxwell makes the status still more explicit:

“This representation involves no physical theory, it is only a kind of artificial notation.”

Again, a later reader has to resist turning the sentence into formalism in the twentieth-century sense.

Maxwell wanted physical theory.

But here he distinguishes the mathematical representation from one.

The representation is useful even while its physical referent remains unclear.

One paper, more than one representational level

This is one of the most important facts in the chapter.

On Faraday's Lines of Force does not operate with one fixed epistemic status.

The imaginary fluid is explicitly nonliteral.

The electrotonic functions are described as artificial notation.

Physical analogy connects domains without asserting physical identity.

At other moments Maxwell discusses what a future physical theory would have to explain.

Different representational tools coexist.

That is more precise than simply saying “Maxwell used models”.

Weber's rival theory

Near the end of the paper Maxwell confronts a very different possibility.

Wilhelm Weber had constructed a mathematically powerful electrodynamic theory in which electrical particles acted directly upon one another according to a force depending on distance and relative motion.

Maxwell does not dismiss it.

He calls it “a really physical theory, satisfying the required conditions better perhaps than any yet invented”.

That makes his response more revealing.

Why continue developing another representation when a strong rival exists?

Maxwell also records a specific objection: “There are also objections to making any ultimate forces in nature depend on the velocity of the bodies between which they act.” The same family of objection reappears in his 1865 discussion of the mechanical difficulties of velocity-dependent action at a distance.

Two ways of looking

Maxwell answers:

“it is a good thing to have two ways of looking at a subject, and to admit that there are two ways of looking at it.”

This is Maxwell’s own published statement, not a later recollection.

It occurs in the closing portion of *On Faraday’s Lines of Force* itself.

Plurality of representation is being defended while the physical theory remains unsettled.

A temporary theory

Maxwell continues:

“I do not think that we have any right at present to understand the action of electricity...”

Then comes the sentence that is unusually important for this book:

“the chief merit of a temporary theory is, that it shall guide experiment, without impeding the progress of the true theory when it appears.”

The wording has two sides.

A temporary theory should guide experiment.

It is not idle speculation.

But it should not obstruct a better theory merely because its imagery has become familiar.

Usefulness and permanent truth are not identical.

Temporary theory has a positive role

The closing sentences go further than the earlier warning about premature theory.

Maxwell explicitly assigns a positive role to temporary theory.

It can guide experiment.

And he explicitly defends maintaining more than one way of representing the subject.

Not yet a uniquely Maxwellian method

It would be easy to stop here and announce the book's thesis.

That would be premature.

William Thomson had already used mechanically suggestive analogies while withholding commitment to their literal physical truth.

William Rankine had explicitly distinguished hypothetical and abstractive theories and defended hypothetical theory as a preliminary tool.

Maxwell's remarks therefore belong to a broader Victorian debate over analogy, mechanism and representation.

The comparative question remains open.

What Maxwell took from Thomson

Maxwell identifies Thomson as an important source for his mathematical treatment.

In the introduction to *On Faraday's Lines of Force* he writes that the analogy between the formulae of heat and attraction had, he believed, first been pointed out by William Thomson.

Elsewhere in the paper he explicitly cites Thomson's 1847 *On a Mechanical Representation of Electric, Magnetic and Galvanic Forces*.

The connection is therefore documentary, not merely parallel.

By 1855–56 Maxwell had read the same mechanical-representation paper whose accompanying letter to Faraday later serves in this book as a control on Maxwell's own use of analogy.

That does not make Maxwell's later method an inheritance reducible to Thomson.

It does prevent a story in which Maxwell invents physical analogy in isolation.

What Maxwell took from Faraday

Faraday's contribution is different.

The lines of force are not merely decorative geometry applied after a mathematical theory already exists.

They organise the physical phenomena Maxwell is trying to preserve mathematically.

The electrotonic state poses another problem: a physically suggestive condition exists in Faraday's work before Maxwell has a satisfactory mathematical and mechanical account of it.

Maxwell translates.

But translation changes the object.

The translation creates new possibilities

Once Faraday's physical relations have mathematical form, Maxwell can compare them with other mathematical systems.

He can calculate limiting cases.

He can ask whether rival theories produce the same observable consequences.

He can transport mathematical relations from one physical analogy to another.

The representation becomes an instrument of further research.

That is exactly the positive role Maxwell gives temporary theory.

Faraday does not disappear

It is tempting to narrate this as mathematics replacing Faraday's intuition.

The later electromagnetic theory makes that story especially attractive.

But Maxwell repeatedly returns to Faraday's physical language.

The lines remain.

Dielectric polarisation remains important.

In 1865 Maxwell explicitly acknowledges Faraday's 1846 *Thoughts on Ray-Vibrations* when discussing the electromagnetic theory of light.

Faraday remains an intellectual co-protagonist, not a pre-mathematical preliminary.

A productive incompleteness

The electrotonic state supplies a useful case of incomplete understanding.

Maxwell can write equations involving a quantity whose nature he says he cannot yet explain clearly without symbols.

This is not ignorance disguised as knowledge.

The limitation is stated.

The mathematics still carries experimentally meaningful relations.

Physics can therefore possess a disciplined partial representation before possessing a satisfactory mechanism.

More than a billion kilometres away

The next major problem in the book could hardly look more different.

Saturn lies more than a billion kilometres from Earth even at relatively close opposition.

Its rings could not be touched, sampled or mechanically tested.

Yet Maxwell would reach a strong conclusion about their physical constitution.

The route would not be analogy in the same form.

It would be elimination through dynamics.

The change of subject is deliberate.

If there is a unity in Maxwell's reasoning, it must survive a change this large.

What Chapter 5 establishes

By 1856 we can document several distinct positions.

A physical analogy can calculate without being literally true.

A mathematical representation can be useful even when Maxwell lacks a clear physical interpretation for it.

More than one representation of the same phenomena can be scientifically valuable.

A temporary theory can guide experiment without deserving permanent commitment.

Those claims are now anchored in Maxwell's own published text.

The question is no longer whether he sometimes worked this way.

He did.

The harder question is whether this was distinctively Maxwellian.

For that, we need comparison.

And we need other domains.

Saturn supplies the next one.

Chapter 6

Saturn: What Cannot Be Stable

Saturn can be seen.

Its rings cannot be handled.

In Maxwell's time, even their basic physical constitution remained uncertain.

Were they solid?

Fluid?

Cloud-like?

Made from separate bodies?

The answer could not be obtained by travelling there.

It had to be inferred from what different possible ring systems could and could not do.

The problem was given to Maxwell

The first correction is one of authorship.

Maxwell did not invent the three-way comparison that structured the problem.

The examiners for the Adams Prize did.

The Adams Prize problem was announced on 23 March 1855.

The announcement instructed candidates to consider three possible physical constitutions:

a rigid ring;

a fluid or partly aeriform ring;

and a ring consisting of masses not mutually coherent.

The candidates were to ask, for each hypothesis separately, whether the attractions and motions of Saturn and the rings could satisfy the conditions of mechanical stability.

The comparison space therefore came from the prize question.

Maxwell's contribution lies in what he did inside it.

Stability, not appearance alone

A drawing of Saturn can show what a ring looks like.

It cannot show whether the ring could persist dynamically.

A configuration may be geometrically imaginable and still be unstable.

A perfectly centred rigid ring around a planet is an example.

At one instant, the geometry can look admissible.

The important question is what happens after a small disturbance.

Does the system return?

Remain bounded?

Drift farther away?

Break apart?

Stability turns persistence into evidence.

Laplace had already attacked the solid ring

Maxwell was not the first to recognise the difficulty.

Laplace had already shown that a uniform solid ring centred on Saturn could not remain stable.

Maxwell therefore entered an existing dynamical problem.

The historically useful question is not:

Who first considered a solid Saturnian ring?

It is:

What did Maxwell add?

The uniform rigid ring

A uniform rigid ring is unstable.

If its centre is displaced slightly relative to Saturn, the resulting gravitational forces do not simply restore it.

The displacement can grow.

Symmetry at equilibrium is therefore not enough.

A configuration that is mathematically possible at one instant may be dynamically impossible as a persistent physical system.

Could an irregular rigid ring survive?

Maxwell then examined whether a strongly non-uniform rigid ring might remain stable.

In principle, an appropriate concentration of mass could alter the dynamics.

But stability demanded an extreme irregularity.

Maxwell found that stability would require a satellite about four and one-half times the weight of the ring, an arrangement he called far too artificially adjusted to agree with the natural arrangements observed elsewhere, since a very small excess or defect would render the ring unstable again.

The point is subtle.

He did not show that every imaginable rigid ring is mathematically impossible.

He showed that the stable rigid alternatives required a constitution inconsistent with what the observed system made plausible.

Possibility is not plausibility

This distinction matters throughout the book.

A mathematical construction can exist without being a credible physical description.

The loaded rigid ring is therefore a useful boundary case.

The calculation does not merely ask:

Can equations be written?

It asks whether a dynamically admissible configuration also fits the astronomical object being explained.

The fluid ring

A continuous fluid ring does not escape the stability problem.

Different parts of such a ring would respond differently to Saturn's attraction.

Disturbances propagate through the fluid.

The resulting motions generate waves and redistribute material.

Maxwell's analysis led to the conclusion that a continuous fluid ring could not preserve the observed ring system as a stable continuous body.

Its perturbations would ultimately destroy that continuity.

The fluid hypothesis therefore fails for a different dynamical reason from the uniform rigid ring.

A ring of separate satellites

The third hypothesis changes the problem fundamentally.

Suppose the ring is not one coherent object at all.

Suppose it consists of many independent masses, each orbiting Saturn.

Then neighbouring particles need not share one rigid angular velocity.

Bodies at different distances can revolve at different orbital speeds.

The ring becomes a system of many satellites rather than one continuous mechanical body.

This is the case in which Maxwell's analysis found a viable route to stability.

Waves inside a particulate ring

Even this solution was not trivial.

A ring of independent satellites can be disturbed.

Its particles gravitationally influence one another.

Maxwell therefore analysed waves of disturbance propagating through the ring.

The particulate hypothesis was not accepted merely because it avoided rigidity.

It had to satisfy its own dynamical constraints.

This is where much of the mathematical depth of the essay lies.

The dark ring matters

Dynamics was not the only evidence.

Astronomers had recently identified a faint inner ring, the so-called dark or dusky ring.

Its appearance supplied an additional observational constraint.

Maxwell argued that light passing through such a region could be understood if rays travelled through spaces between separated particles.

A continuous solid or fluid medium would not produce the same interpretation naturally.

The optical evidence and the dynamical analysis therefore pointed in the same direction.

What Maxwell concluded

Maxwell's conclusion was that the rings must consist of an indefinite number of unconnected particles, revolving round the planet with different velocities according to their respective distances.

That conclusion is striking because the particles themselves could not be individually resolved by nineteenth-century telescopes.

Their existence was inferred.

Knowing by impossibility

The reasoning is therefore partly eliminative.

Maxwell does not begin by seeing individual ring particles.

He considers physical constitutions.

Dynamics rules out some of them.

Observation constrains others.

What remains gains credibility.

This is a different way of learning about something invisible.

In Chapter 5, analogy allowed relations to be developed without full commitment to an underlying mechanism.

Here, impossibility removes candidate constitutions.

But Maxwell did not choose the candidates

This distinction must remain visible.

The rigid, fluid and incoherent-mass alternatives were specified by the Adams Prize problem.

Maxwell did not create the test by inventing those three possibilities.

His achievement was:

the depth of the stability analysis;

the treatment of non-uniform rigid rings;

the analysis of disturbances and waves in particulate rings;

and the combination of dynamical elimination with astronomical evidence, including the dark ring.

That is more precise than crediting him with the entire comparative framework.

Against Laplace, not instead of Laplace

The relation to Laplace is similarly layered.

Laplace had already identified instability in the uniform rigid case.

Maxwell extended the investigation much further.

He asked what kinds of non-uniform rigid ring might survive.

He analysed fluid rings.

He developed the particulate case mathematically.

He connected the dynamics to observed features.

Progress here means extending an inherited problem, not replacing an earlier scientist with a later one.

The result was not immediately observable

The conclusion remained inferential.

No nineteenth-century observer watched the individual ring particles orbiting Saturn.

The evidence came from:

the continued existence of the rings;

their observed structure;

the known laws of mechanics;

and the instability of competing constitutions.

This is a particularly clean example of physical knowledge outrunning direct observation.

More than three decades later

In 1895, James Edward Keeler used spectroscopy to examine the motion of different parts of Saturn's rings.

The Doppler shifts showed that the inner portions moved faster than the outer portions.

That is the rotational pattern expected for separate orbiting particles rather than a rigid solid disk.

This later evidence strongly supported the particulate interpretation.

But it must remain later.

Maxwell did not possess Keeler's observation when he wrote the essay.

Later confirmation is not earlier evidence

The distinction is essential.

Keeler can tell us that Maxwell's conclusion survived an independent observational test.

Keeler cannot be placed inside Maxwell's original reasoning.

The history should therefore be told in two stages:

first the nineteenth-century inference from stability;

then the later spectroscopic test.

Saturn did not teach Maxwell kinetic theory

A tempting retrospective story would connect Saturn directly to Maxwell's later molecular physics.

The ring consists of many small particles.

A gas consists of many small molecules.

Both involve collective behaviour.

But structural similarity is not documentary causation.

There is no need to claim that Saturn taught Maxwell how to think statistically.

The two episodes can be compared without inventing a transfer.

What can legitimately be compared

The comparison is still useful.

In both cases, the system contains many constituents that cannot be tracked individually.

But the mathematical tasks differ.

For Saturn, orbital dynamics and stability eliminate physical constitutions.

For gases, probability and velocity distributions describe populations.

Similarity of scale does not imply identity of method.

This is exactly the kind of comparison the book needs if its unity thesis is to remain testable.

Persistence as evidence

Saturn introduces one idea that will return later.

A physical system tells us something by continuing to exist.

If a proposed constitution would quickly destroy itself under small disturbances, the observed persistence of the actual system counts against that constitution.

The absence of catastrophe becomes evidence.

This logic will reappear in other forms.

A governor that returns after disturbance is stable.

A null electrical experiment constrains a force law because an expected effect fails to appear.

What does not happen can be physically informative.

What the Saturn case establishes

The case establishes less than a heroic version would claim, but more than a mere calculation.

Maxwell inherited a structured prize problem.

He inherited Laplace's earlier result.

Within that framework, he developed a deep dynamical analysis that eliminated rigid and continuous-fluid descriptions of the observed system and made a particulate ring the viable physical interpretation.

The constituent particles were not directly seen.

They were inferred from constraints.

Another route into the invisible

Chapter 5 showed a representation whose usefulness could exceed commitment to its literal mechanism.

Chapter 6 shows another strategy.

Sometimes the hidden structure is approached not by constructing one picture, but by discovering which pictures cannot survive.

The two routes are different.

That difference matters.

If the book eventually finds a unity in Maxwell's reasoning, it cannot be because every problem was solved through analogy.

Sometimes Maxwell learned what the invisible world could contain by determining what it could not.

Chapter 7

Molecules Nobody Could Follow

A gas looks simple.

Fill a vessel with air and nothing visible announces the violence supposedly taking place inside it.

There are no obvious projectiles.

No impacts can be seen.

No individual trajectory can be followed.

Pressure appears smooth.

Temperature appears to belong to the gas as a whole.

Yet by the middle of the nineteenth century an increasingly serious physical picture said that this apparent continuity concealed an enormous population of moving particles.

If that picture was right, physics faced a peculiar problem.

The microscopic motions were not merely difficult to observe.

There were too many of them for the usual ideal of mechanical prediction to be useful.

Maxwell's response would transform the problem.

Instead of trying to know every molecule, he would ask how a multitude could be known statistically.

Probability before molecules

Probability did not suddenly enter Maxwell's thinking in 1860.

A letter to Lewis Campbell written in 1850, while Maxwell was still preparing for Cambridge, already contains a striking remark about what he called the "calculus of Probabilities".

The context was not kinetic theory.

That distinction matters.

We cannot use a youthful comment about probability as proof that Maxwell had already conceived statistical physics.

But it establishes that probability belonged to his intellectual vocabulary long before his first paper on gases.

For our purposes, the important question is not whether Maxwell liked probability.

It is what happened when probability became part of a physical theory whose individual components could not be tracked.

A gas made of moving particles

The kinetic theory of gases was older than Maxwell.

Daniel Bernoulli had connected gas pressure with molecular motion in the eighteenth century.

Later investigators, including Herapath, Joule, Krönig and Rudolf Clausius, developed versions of the idea.

Maxwell himself opened the 1860 paper by acknowledging this inheritance:

“Daniel Bernoulli, Herapath, Joule, Kronig, Clausius, &c. have shewn that the relations between pressure, temperature, and density in a perfect gas can be explained by supposing the particles to move with uniform velocity in straight lines...”

That sentence does two things at once.

It acknowledges the predecessors.

And it identifies the simplification Maxwell is about to remove.

The particles had often been treated as though they shared a common speed.

Maxwell's innovation would be to let the population contain a distribution.

Clausius and the collisions

A naïve molecular model creates an immediate problem.

If gas molecules move at very high speeds, why do gases not transport themselves equally rapidly across a room?

Why does diffusion take appreciable time?

Clausius supplied an essential answer.

A molecule may move rapidly while travelling only a short distance before colliding with another molecule.

Its trajectory therefore changes repeatedly.

Rapid microscopic motion does not imply rapid macroscopic transport in one direction.

Maxwell explicitly acknowledged this contribution:

| “M. Clausius has determined the mean length of path...”

The phrase is brief.

Its importance is not.

Once collisions dominate the microscopic picture, following one molecule becomes even less attractive as a method.

Its path is repeatedly interrupted.

The state of one particle becomes entangled with the statistical state of many others.

The gas is still mechanical.

But its useful description need not be a complete mechanical history.

Maxwell enters the problem

Maxwell was reading Clausius while developing his own kinetic theory in 1859.

The surviving correspondence with Stokes establishes that context.

The theory was first presented at the British Association meeting in Aberdeen in September 1859 and appeared in two parts in the Philosophical Magazine in 1860.

The comparison with Clausius remains essential.

Clausius had already made collisions central.

Maxwell's contribution was not to replace a static gas with moving molecules.

It was to ask a different question about those molecules.

Must they all have the same speed?

The simplification that had to go

The uniform velocity assumption made calculation manageable.

But collisions make such a state difficult to preserve.

Even if every molecule began with the same speed, collisions occurring at different angles would redistribute motion among components and among particles.

The natural state of the gas should therefore contain a range of velocities.

This sounds obvious now because the Maxwell distribution is already familiar.

It was not obvious before someone made the distribution itself part of the theory.

That was Maxwell's decisive step.

Not one velocity, but a population

In *Illustrations of the Dynamical Theory of Gases*, Maxwell considered a very large number of perfectly elastic spherical particles undergoing collisions.

After sufficiently many encounters, he argued, the particles should settle into a regular statistical distribution of velocities.

The object of calculation changes at this point.

We no longer ask:

What is the velocity of the molecule?

We ask:

How many molecules have velocities within a given range?

That is a profound change in the level of description.

The individual mechanical trajectory has not been declared nonexistent.

It has become the wrong object for the question.

A physical analogy under test

But Maxwell was careful about what his model established.

He did not begin by declaring that real gases literally consisted of perfectly elastic spheres obeying exactly the assumptions of his calculation.

He wrote:

“If the properties of such a system of bodies are found to correspond to those of gases, an important physical analogy will be established.”

That sentence fixes the epistemic status of the 1860 model.

Molecules as such were already taken seriously by many physicists.

Maxwell's particular system of perfectly elastic spherical particles was something more specific.

Its relation to actual gases had to be tested.

The model was not the gas.

It was a candidate physical analogy whose success depended on correspondence with observable properties.

Three components

Every molecular velocity can be decomposed into three perpendicular components.

Maxwell used x , y and z for these components.

His crucial assumption was that:

“the existence of the velocity x does not in any way affect that of the velocities y or z , since these are all at right angles to each other and independent...”

Together with isotropy, this makes the distribution factorise.

The resulting component distributions have the familiar bell shaped form, from which the distribution of molecular speeds follows.

Today the mathematical result is so familiar that the originality of the representational move can disappear.

A physical state was now being described by a distribution.

Maxwell later questions his own assumption

The derivation should not be made cleaner by hindsight.

The independence assumption is not a timeless theorem of mechanics.

Maxwell himself returned to it.

In 1867 he wrote:

“As this assumption may appear precarious, I shall now determine the form of the function in a different manner.”

This is stronger historical evidence than simply saying that later mathematicians criticised the derivation.

A caution comes from Maxwell himself, in 1867.

A result he had introduced successfully could remain valuable while the route by which he first obtained it required reconsideration.

That pattern will matter repeatedly in this book.

The distribution is not ignorance alone

Why use probability?

One possible answer is merely practical:

because we cannot know all the molecular velocities.

That answer is insufficient.

A probability distribution does more than confess ignorance.

It generates quantitative predictions about collective behaviour.

From a distribution one can calculate average quantities.

One can ask about pressure.

Transport.

Collisions.

Viscosity.

Thermal conduction.

Diffusion.

Statistical representation therefore adds structure rather than simply discarding microscopic information.

The inaccessible details are replaced by measurable regularities at another level.

An enormous compression

Imagine recording the complete mechanical state of a gas.

For every molecule one would need at least a position and a velocity.

For an ordinary macroscopic amount of gas, the number of variables would be astronomical.

And the state would immediately change as collisions occurred.

A distribution performs an extraordinary compression.

Instead of following every molecule, physics describes how a population is spread across possible velocities.

Individual identity is discarded.

Statistical structure remains.

This is not simply a mathematical convenience.

It changes what counts as a satisfactory physical description.

Mechanics without complete trajectories

Classical mechanics is often associated with the ideal that, given exact initial conditions and exact laws, future motion is in principle calculable.

Kinetic theory does not necessarily deny that ideal at the molecular level.

But it exposes a difference between in-principle mechanical determination and useful physical prediction.

Even if every collision obeys mechanics exactly, a macroscopic gas may be described far more effectively through distributions and averages.

The theory therefore introduces probability without first requiring microscopic indeterminism.

That point must be protected from twentieth-century hindsight.

Maxwell's probabilities should not be converted retrospectively into quantum uncertainty.

The molecules in his 1860 theory are classical mechanical objects.

The novelty lies in the level at which the population is described.

From hidden bodies to visible pressure

The molecular picture is inaccessible directly.

Pressure is not.

A gas exerts force on the walls of its container.

Within kinetic theory, that smooth macroscopic pressure can be related to an enormous number of microscopic impacts.

Once again, the visible or measurable quantity does not resemble the hidden process producing it.

Pressure is not a tiny impact enlarged.

It is a collective quantity emerging from many impacts.

This is a different kind of bridge between hidden structure and observation from the ones we have already encountered.

In strained glass, mechanical state produced an optical signal.

In colour, physical stimuli produced perceptual matches.

At Saturn, stability eliminated possible constitutions.

In a gas, smooth macroscopic behaviour is reconstructed from a multitude of microscopic events no observer can follow individually.

What Clausius had already accomplished

The comparison with Clausius needs to remain strong.

Clausius had already connected molecular motion to macroscopic thermodynamic properties.

He had made collisions central.

He had developed the mean path.

He had treated internal molecular motion in ways that went beyond the simplest point particle model.

Maxwell's achievement was therefore not kinetic theory itself.

The sharper claim is this:

he introduced a statistical distribution of molecular velocities into kinetic theory and began deriving measurable gas properties from that distribution.

That is where the historical shift lies.

Collisions and statistical regularity

There is a conceptual tension inside the theory.

Collisions complicate individual trajectories.

Two particles approach.

They strike.

Their directions change.

Repeat this across an enormous population and the microscopic history becomes increasingly difficult to track.

Yet Maxwell expected the population to exhibit a regular statistical distribution.

Complicated individual motion could coexist with simple collective regularity.

That is an important idea.

But Maxwell's 1860 argument should not be silently upgraded into the later Boltzmannian account of equilibration.

The stages must remain distinct.

Boltzmann is not yet here

The phrase Maxwell-Boltzmann distribution invites another distortion.

It puts two names together so naturally that they can appear to have belonged to one collaboration or one simultaneous theory.

They did not.

Ludwig Boltzmann was younger.

His major kinetic and statistical work followed Maxwell's initial distribution and developed the subject in directions Maxwell had not yet taken.

Their work would later interact.

At this stage of the narrative, in 1860, we are looking at Maxwell's distribution.

Boltzmann belongs later.

Viscosity: the startling result

Maxwell used the molecular model to investigate transport properties.

One prediction was especially striking.

The coefficient of viscosity should be independent of the density of the gas.

Maxwell knew how surprising this was.

He wrote:

“the coefficient of friction is independent of the density. Such a consequence of a mathematical theory is very startling...”

But the next clause is just as important:

“...and the only experiment I have met with on the subject does not seem to confirm it.”

This changes the historical texture of the result.

In 1860, density-independent viscosity was not presented as a clean theoretical triumph awaiting later experimental confirmation.

Maxwell explicitly published it while acknowledging that the only experiment known to him appeared to disagree.

The model generated a bold result.

The available evidence did not yet support it.

A theory reports against itself

That sentence is important beyond viscosity.

Maxwell did not hide the mismatch.

He placed it inside the paper.

The result therefore becomes an unusually clear example of theory operating under evidentiary pressure.

The theory says one thing.

The known experiment appears to say another.

Maxwell retains the calculation and records the conflict.

Later experiments will change the evidentiary situation.

But that later success must not be imported backward into 1860.

The specific-heat failure is already there

The paper contains an even deeper problem.

Maxwell considered particles more complicated than simple spheres, allowing energy to be shared between translational and rotational motion.

The resulting prediction failed against the known relation between the two specific heats of gases.

Maxwell wrote that:

“a system of such particles could not possibly satisfy the known relation between the two specific heats of all gases.”

He gave the observed ratio as approximately 1.408.

This is not a difficulty that emerged years later.

It is present in the first kinetic paper.

The model succeeds in producing a velocity distribution and important transport results while simultaneously failing in another fundamental thermodynamic comparison.

That is the unevenness of theory in its clearest form.

Success and failure in the same paper

The 1860 paper therefore cannot be narrated as:

distribution first,

triumph,

problems later.

Its structure is more interesting.

Maxwell introduces a powerful statistical representation.

He derives nontrivial consequences.

One consequence conflicts with the only relevant experiment he knows.

Another construction fails against the known specific-heat relation.

And he publishes all of this together.

The paper is both an advance and a record of its own limitations.

That is precisely why it matters for this book.

What survives?

The failures do not erase the velocity distribution.

Nor does the survival of the distribution make the hard-sphere model correct in every respect.

Different pieces of the theory already have different futures.

The statistical representation proves durable.

The model of intermolecular interaction will change.

The treatment of specific heats will remain troublesome.

The viscosity prediction will later receive stronger experimental support, but its temperature dependence will create another problem.

The theory is neither simply right nor simply wrong.

Its components separate.

A distribution describes what no one sees

No nineteenth-century experimenter could observe Maxwell's full velocity distribution molecule by molecule.

The distribution was inferred through theoretical structure and through the collective consequences it generated.

That might seem to make it less physical than a visible trajectory.

But physics had already learned that observability and physical usefulness are not identical.

A quantity can be inaccessible directly and still enter a tightly constrained network of measurable relations.

Kinetic theory adds something new:

the hidden object is not merely one invisible mechanism. It is an entire population.

The individuality disappears

A striking feature of statistical description is what it throws away.

Which molecule has which velocity?

For many macroscopic questions, it does not matter.

Exchange the identities of two otherwise identical molecules and the distribution does not change.

The theory deliberately ignores individuality.

That is not because individual molecules have ceased to exist in the model.

It is because the macroscopic property being calculated does not depend on their names.

Knowing less about each particle can allow one to know more about the gas.

Is probability physical?

A harder question follows.

What exactly does the probability distribution mean?

Is it a description of actual frequencies within an enormous population?

Is it a representation of incomplete knowledge?

Is it a mathematical device justified by symmetry?

How do collisions produce or sustain the distribution?

Maxwell's 1860 paper does not settle all these questions.

Nor should we pretend that the later foundations of statistical mechanics were already present.

Probability was now doing substantive physical work before its interpretation was fully secure.

Herschel and Quetelet

The mathematical form Maxwell obtained had a history outside kinetic theory.

Related bell shaped distributions belonged to the theory of errors and statistical work associated with figures such as John Herschel and Adolphe Quetelet.

Historians have investigated whether those traditions influenced Maxwell's derivation.

The possibility is historically plausible, but the documentary route of influence remains unresolved.

But the awareness rule remains in force.

A similar mathematical form does not establish a route of influence.

Unless Maxwell's reading or use of those sources is demonstrated, Herschel and Quetelet belong to the comparison and genealogy problem, not to a documented causal narrative.

Availability is not awareness.

Similarity is not influence.

Saturn and molecules

The proximity to Maxwell's Saturn work is equally tempting.

In one problem a seemingly continuous ring was analysed as many separate orbiting bodies.

In another a seemingly continuous gas was analysed as many moving molecules.

The structural resemblance is obvious to us.

It must not be converted automatically into a causal sequence inside Maxwell's mind.

For now they can be placed beside each other.

Saturn asks how a multitude can produce a persistent macroscopic structure.

Kinetic theory asks how a multitude can produce statistical regularity.

Whether Maxwell himself connected those questions in the way we do remains a documentary question.

Three dated hedges

A pattern is beginning to appear, but it should be recorded rather than concluded.

In 1855 Maxwell introduced an imaginary fluid while stating that it was "not even a hypothetical fluid which is introduced to explain actual phenomena".

In 1860 he described his system of elastic particles as a physical analogy whose correspondence with gases remained to be established.

In 1861 he said that the idle-wheel connexion was not one to which he would willingly assent as an electrical hypothesis.

Three dates, two domains.

Three dated cautions.

The resemblance is historically significant.

But whether it constitutes a distinctively Maxwellian method, rather than a broader nineteenth-century practice shared with figures such as Thomson and Rankine, remains for later comparison.

The Epilogue, not this chapter, should decide.

What can be known without following?

The deepest shift in the chapter can now be stated.

Mechanics had traditionally gained much of its explanatory power from trajectories.

Where will the planet go?

How will the projectile move?

What orbit follows from the force?

Kinetic theory confronts a system where trajectories exist in principle but cannot serve as the primary useful description.

There are simply too many.

Maxwell's solution was not to abandon mechanics.

It was to change the object of knowledge.

Do not predict each molecule.

Predict the distribution.

Do not demand the full microscopic history.

Calculate the collective regularity.

That change opened a new route to the invisible.

Not a clean victory

By the end of 1860, Maxwell had not solved kinetic theory.

He had created a statistical representation of enormous power.

He had also published evidence that parts of the model did not yet agree with what was known.

The conflict over viscosity would later change.

The specific-heat problem would deepen.

The intermolecular force law would be revised.

And Maxwell himself would revisit the derivation of the distribution.

This is not a blemish on the achievement.

It is part of the achievement's actual historical form.

One representation among several

By 1860 Maxwell's scientific work already contained an extraordinary variety of representations.

Geometrical curves.

Optical patterns.

Colour matching equations.

Faraday's lines.

An imaginary fluid.

Electrotonic components.

Collections of orbiting particles.

Now a probability distribution over molecular velocities.

The list is suggestive.

But suggestion is not demonstration.

The 1860 gas model itself warns us against drawing the contrast too sharply.

Perfectly elastic spheres were also offered as a physical analogy under test.

In electromagnetism, other models would likewise carry different levels of commitment.

The important question is therefore not:

Which models did Maxwell believe, and which did he merely invent?

It is more difficult:

How did he distinguish among the parts of a representation that were empirically constrained, provisionally useful, mechanically conceivable, or still unproved?

That question now carries us back into electromagnetism.

The next construction will first build the mechanical medium; displacement, elasticity and propagation will follow after that.

And it will eventually produce a number that forces Maxwell to compare electricity with light.

Chapter 8

Vortices, Idle Wheels and a Mechanically Conceivable Medium

In 1855 Maxwell had introduced an imaginary fluid and immediately warned his reader not to mistake it for a physical explanation.

Six years later he did something much more dangerous.

He filled the magnetic field with rotating matter.

The change matters.

The fluid in On Faraday's Lines of Force had been deliberately artificial. Its purpose was to carry mathematical relations from hydrodynamics into electricity and magnetism.

The machinery of On Physical Lines of Force was different.

There were vortices.

There were stresses.

There were intermediate particles.

There was rotational motion.

There was something resembling a mechanical transmission system built into the medium itself.

And Maxwell wanted to know whether such machinery could account mechanically for known electromagnetic effects.

This is the point at which the phrase "Maxwell's mechanical model" becomes both useful and dangerous.

Useful, because the model is unmistakably mechanical.

Dangerous, because the paper does not assign the same status to every component.

That distinction is the key to understanding what follows.

Stress before machinery

Maxwell did not begin by drawing an elaborate microscopic machine and then asking what electromagnetic effects it might imitate.

He began with the mechanical stresses required in a magnetic medium.

The direction of magnetic force throughout a region implied an anisotropic stress.

A mechanical representation would therefore have to reproduce the correct resultant forces along and across the magnetic lines.

Rotational motion offered one possible cause.

A vortex generates centrifugal stress.

A system of vortices aligned with the magnetic lines could therefore reproduce the directional stresses associated with magnetic action.

The order matters.

First comes the stress relation.

Then comes a proposed cause of that stress.

Maxwell himself later makes the distinction explicit.

The mechanical stress corresponding to the electromagnetic force, he writes, is valid:

“independently of any particular theory as to the cause of this state of stress, or the mode in which it can be sustained in the medium.”

That sentence should govern the entire chapter.

The stress relation and the mechanism proposed to sustain it do not possess the same evidentiary status.

Molecular vortices

Maxwell imagined the magnetic medium as filled with vortices of rotating matter whose axes followed the magnetic lines of force.

Magnetic intensity corresponded to rotational velocity.

Properties associated with magnetic induction entered through properties assigned to the rotating medium.

The model translated electromagnetic quantities into mechanical ones.

Magnetic intensity became rotation.

Magnetic stress became centrifugal stress.

The invisible electromagnetic state acquired mechanically imaginable contents.

But the word imaginable is crucial.

A mechanism can make relations intelligible without every feature of the mechanism being independently established.

Rankine was already using vortices

Even molecular vortices did not belong uniquely to Maxwell.

W. J. Macquorn Rankine had developed a substantial vortex programme before Maxwell's electromagnetic construction.

Rankine stated that his researches on the mechanical action of heat had begun in 1842, and in 1855 he published explicitly on the hypothesis of molecular vortices in relation to elasticity and heat.

His vortices were not Maxwell's vortices.

The detailed physics and the phenomena being explained differed.

But Rankine matters as a comparison because he shows that vortical microscopic mechanisms already belonged to the conceptual resources of British mathematical physics.

There is currently no verified documentary basis for saying that Maxwell took the idea from Rankine.

The accessible text of *On Physical Lines of Force* does not name him.

Similarity is therefore not influence.

Rankine belongs here as parallel practice.

Thomson enters directly

William Thomson occupies a different evidentiary position.

Maxwell cites him.

Thomson had already worked with mechanical representations of magnetic and optical effects and had explicitly separated mathematical analogy from commitment to physical theory.

More importantly, in Part IV of *On Physical Lines of Force*, Maxwell invokes Thomson's argument concerning the magneto-optic effect.

Maxwell writes that Thomson had pointed out that the magnetic action on light required:

“a real rotation going on in the magnetic field.”

Maxwell then adds that the direction of rotation is connected with the direction of the magnetic lines in a way that:

“seems to indicate that magnetism is really a phenomenon of rotation.”

This is stronger language than the paper uses for some other components of the mechanism.

And it appears in Part IV, after the earlier stress construction.

Chronology matters.

The rotation hypothesis did not enter the whole paper with one fixed evidentiary status.

It acquired additional support as Maxwell connected it with the magneto-optic problem.

The problem of neighbouring vortices

A mechanical difficulty appears immediately.

Adjacent vortices rotating in the same general sense would have neighbouring surfaces moving in opposite directions.

If the vortices touched directly, they would interfere mechanically.

Maxwell needed a form of connexion between them.

His solution was to place small particles between the vortices.

He made the mechanical analogy explicit:

“In mechanism, when two wheels are intended to revolve in the same direction, a wheel is placed between them so as to be in gear with both, and this wheel is called an ‘idle wheel.’”

Maxwell then proposed layers of particles acting as such idle wheels between neighbouring vortices.

The term therefore belongs to Maxwell’s own mechanical description, not to later textbook shorthand.

The idle-wheel disclaimer

Yet Maxwell explicitly refuses to present this connexion as something established in nature.

He writes:

“I do not bring it forward as a mode of connexion existing in nature, or even as that which I would willingly assent to as an electrical hypothesis.”

He continues that it is nevertheless:

“a mode of connexion which is mechanically conceivable, and easily investigated”

and adds that anyone who understands:

“the provisional and temporary character of this hypothesis”

may be helped rather than hindered by it.

This is one of the most important pieces of evidence in the entire paper.

The idle-wheel machinery is not merely uncertain.

Maxwell explicitly withholds assent to it even as an electrical hypothesis.

Its value lies in mechanical conceivability and calculational usefulness.

Electricity enters the machinery

The intermediate particles nevertheless perform substantial work inside the model.

Their translational motion represents electric current.

Their interaction with the vortices transmits rotational effects.

Tangential forces correspond to electromotive action.

When these particles pass from one molecular region to another, Maxwell writes that they may:

“experience resistance, so as to waste electrical energy and generate heat.”

The model therefore links current, resistance and heat inside one mechanical construction.

Its weak ontological status does not make it scientifically idle.

A provisional mechanism can still generate structured consequences.

Arbitrary direction

Not every feature of the vortices is forced by the physics.

Maxwell explicitly says:

“We also assumed, perfectly arbitrarily, that the direction of these vortices is such that...”

The direction convention is therefore representational.

It is not presented as a discovered fact about the invisible medium.

This matters because it shows that the model contains features of different kinds.

Some are constrained by the electromagnetic relations.

Some are choices required to complete the representation.

A model is therefore not a single block of equally supported claims.

Indeterminate size

The same is true of scale.

Maxwell writes:

“The size of the vortices is indeterminate, but is probably very small as compared with that of a complete molecule of ordinary matter.”

The first clause is crucial.

The theory does not determine their size.

The second is a speculation about likely scale.

The vortices therefore occupy an inaccessible region without being fixed quantitatively by the model.

Again, the component carries weaker evidence than the stress relations it helps represent.

Five epistemic layers

The paper can now be separated into at least five layers.

1. Electromagnetic stress relations

These survive independently of a particular mechanical cause.

1. Rotation in the magnetic field

This is treated more seriously and later gains support through Thomson's magneto-optic argument.

1. Idle-wheel connexion

This is explicitly provisional, mechanically conceivable and not something Maxwell says he would willingly accept as an electrical hypothesis.

1. Direction convention

This is chosen arbitrarily.

1. Microscopic scale

This remains indeterminate.

This hierarchy is more faithful to Maxwell than asking whether he “believed the vortex model”.

There was no single belief status to assign.

Did Maxwell believe in the vortices?

The question can now be asked more carefully.

Did Maxwell believe that something genuinely rotational occurred in the magnetic field?

By Part IV, his language suggests a real commitment to rotation, stated with some caution: it “seems to indicate” that magnetism is really a phenomenon of rotation.

Did he believe that the detailed idle-wheel mechanism literally existed?

No.

His own disclaimer explicitly withholds that assent.

Did he believe the stress relations were valid?

He explicitly says they do not depend on a particular theory of their mechanical cause.

Did he know the size or direction convention of the microscopic vortices?

No.

The text itself grades the components.

The historian should not flatten them again.

Rankine as a harder comparison

This sharpening also improves the comparison with Rankine.

Rankine had already distinguished objective hypotheses, adopted as probable representations of things that might actually exist, from subjective hypotheses, used as convenient ways of expressing the laws of phenomena.

He also argued that hypothetical theory could serve as a necessary preliminary step toward an abstractive theory.

Those are Rankine's own categories.

They already show that a contemporary could distinguish different levels of commitment within hypothetical modelling.

The question for later comparison is therefore narrower.

Did Rankine also grade the components of his own vortex mechanisms as explicitly as Maxwell does here?

That question has to be answered from Rankine's vortex papers themselves.

We should not answer it from retrospective obituary commentary.

Mechanical conceivability

Why construct idle wheels if Maxwell did not want to assent to them as real electrical machinery?

Because they make the connexion mechanically conceivable.

That phrase matters.

Nineteenth-century physical explanation often demanded more than formal equivalence.

A theory could reproduce equations yet leave the causal process obscure.

Mechanical representation supplied a sequence of actions:

rotation,

contact,

translation,

stress,

resistance,

heat.

One could picture how one process gave rise to another.

The mechanism therefore performed conceptual and calculational work even if it was provisional.

A governor inside the electromagnetic machine

In explaining how idle wheels can transmit motion while their centres move, Maxwell gives a concrete mechanical example: Siemens's governor for steam engines.

That reference is worth preserving for later.

It establishes that governor mechanisms were already part of Maxwell's mechanical repertoire in 1861, seven years before *On Governors*.

It does not establish that he transferred a common method from electromagnetism to control theory, or vice versa.

For now, it is simply a documented point of contact.

Its significance, if any, belongs to the later stability chapter.

The cost of mechanical richness

Every added mechanism creates additional assumptions.

The medium must possess mechanical properties.

The vortices need rotational inertia.

The intermediate particles need constraints.

Resistance requires a way for their motion to be impeded.

Heat requires another form of motion or energy transfer.

The explanatory machine becomes increasingly elaborate.

That richness creates power.

It also creates vulnerability.

A model with many physical commitments has many possible points of failure.

Rotation is not the same as idle wheels

This distinction will be essential later.

The failure of the detailed intermediate mechanism would not automatically eliminate the idea of rotation.

The abandonment of microscopic cog-like connexion would not automatically eliminate the stress relation.

The disappearance of the entire mechanical picture would not automatically eliminate the equations derived from it.

Different layers can survive differently.

That is precisely why the paper cannot be classified as one indivisible mechanical hypothesis.

A sequence of strengthening and weakening

The chronology inside *On Physical Lines of Force* now becomes analytically useful.

In the early construction, mechanical vortices provide a possible cause of magnetic stress.

The idle-wheel machinery is openly provisional.

Later, the magneto-optic evidence gives the rotational element a stronger physical claim.

This means the model is not merely assembled once and then defended.

Its internal evidentiary balance changes during the sequence of the paper.

That is exactly the kind of documentary transformation this book is trying to follow.

What survives if the machine fails?

The most important question can now be stated without ambiguity.

If the idle wheels disappear, what remains?

The stress relation may remain.

The mathematical relation between magnetic intensity and rotation may remain in transformed form.

The empirical connection between magnetism and optical rotation remains.

The particular mode of connexion does not need to survive with them.

This possibility is no longer merely an interpretation imposed from outside.

The paper itself tells us that one layer is independent of the particular cause sustaining the stress and another is explicitly temporary.

That gives the later history a concrete test.

Toward elasticity

The vortex construction still lacks something essential.

To connect electromagnetism with light, a disturbance must be able to propagate.

The medium must therefore respond to displacement.

It must store and return energy.

It must possess a form of elasticity.

That requirement transforms the model again.

Maxwell now has to ask what happens when the intermediate electrical particles are displaced from their equilibrium positions.

If displacement produces a restoring force, the medium can store energy.

If neighbouring regions interact appropriately, disturbances can propagate.

This is the route toward one of the most consequential calculations in nineteenth-century physics.

And the historical order matters enormously.

Maxwell did not begin with a modern capacitor argument and then add a displacement current to preserve charge conservation.

He reached electrical displacement through the mechanics of a polarizable and elastic medium inside this evolving model.

The next chapter begins there.

What should survive?

The vortex theory leaves us with a more precise version of the book's central question.

A physical theory can contain:

observed phenomena,

mathematical relations,

stress relations independent of mechanism,

a physical hypothesis with some empirical support,

provisional machinery,

arbitrary conventions,

and undetermined microscopic properties.

These layers need not share the same fate.

That is what makes the later dismantling of Maxwell's machinery historically interesting.

The question is not simply whether the vortices were true.

It is:

which parts of the construction did later physics need to keep in order to keep the successful relations?

The next transformation begins when the medium is allowed to yield.

Not by flowing away.

By being displaced.

And by pushing back.

Chapter 9

Displacement and the Elastic Medium

An insulator does not conduct.

That sounds simple.

Apply an electrical force to a metal and electricity can move through it. Apply the same kind of force across glass, air or another good insulator and no sustained conduction current crosses the material.

But something still happens.

Electrical influence is transmitted.

A Leyden jar can be charged.

Different insulating materials can behave differently even when each prevents ordinary conduction.

For Maxwell, that difference became one of the routes by which the medium itself entered electromagnetic dynamics.

The historical route matters because the modern story is usually told backward.

Today one can introduce displacement current through a charging capacitor, write a modern form of Ampère's law, observe a problem with continuity and insert the missing term.

That is mathematically efficient.

It is not Maxwell's route.

In Part III of *On Physical Lines of Force*, published in January 1862 after Parts I and II had appeared in 1861, the route runs through Faraday's dielectric induction, electrical polarisation, an elastic medium and the mechanical vortex construction.

To understand what Maxwell did, we have to follow that route rather than replace it with ours.

Faraday's dielectric

Faraday had already made insulating matter physically important.

During his investigations of electrostatic induction in the 1830s, he found that different insulating substances could affect induction differently.

The region between charged conductors was therefore not behaving as a passive geometrical gap.

The material filling it mattered.

Faraday treated dielectric action through a polarised state of the intervening matter.

Maxwell inherited that physical problem.

In a conductor, electricity can pass continuously.

In a dielectric, electrical action can be transmitted while ordinary conduction is prevented.

How could those two responses belong to one physical framework?

Two properties, not one

Maxwell begins by distinguishing conduction from dielectric behaviour.

He writes:

“A conducting body may be compared to a porous membrane which opposes more or less resistance to the passage of a fluid, while a dielectric is like an elastic membrane which may be impervious to the fluid, but transmits the pressure of the fluid on one side to that on the other.”

Two materials can be equally good insulators and still act differently as dielectrics.

The distinction is essential.

A dielectric is not merely a poor conductor.

It possesses another electrical response.

The mechanical comparison already suggests what sort of response Maxwell has in mind.

A porous body allows passage.

An elastic body can deform without allowing passage.

Conduction dissipates.

Elastic displacement can store and return.

Polarisation without continuous transport

Maxwell then adopts Faraday's polarisation picture.

He writes:

“In a dielectric under induction, we may conceive that the electricity in each molecule is so displaced...”

One side of the molecule becomes positively electrical and the other negatively electrical.

The picture is microscopic.

But the displacement can be represented throughout the dielectric.

A general electrical displacement therefore exists even though electricity is not continuously passing from molecule to molecule as in conduction.

The distinction is crucial.

Displacement is not ordinary current.

Once it reaches a fixed value, it remains fixed.

But while it is changing, the situation is different.

Maxwell continues:

“This displacement does not amount to a current, because when it has attained a certain value it remains constant, but it is the commencement of a current, and its variations constitute currents in the positive or negative direction, according as the displacement is increasing or diminishing.”

This is the historical doorway to what later physics isolates as displacement current.

Not a defect in a modern equation.

A changing polarisation inside a dielectric.

Relation and mechanism separate

Maxwell then says something methodologically decisive:

“These relations are independent of any theory about the internal mechanism of dielectrics...”

The relation between electromotive force and displacement is not made logically dependent on a complete microscopic account.

But Maxwell does not stop there.

He immediately adds that when electromotive force produces displacement and the dielectric recovers with an equal electromotive force:

“we cannot help regarding the phenomena as those of an elastic body, yielding to a pressure, and recovering its form when the pressure is removed.”

The two statements belong together.

The relations are independent of a microscopic theory.

The phenomena nevertheless invite a strong elastic interpretation.

Once again Maxwell’s own text grades the representational layers.

Elasticity enters in Part III

The chronology inside the paper matters.

Elasticity of figure should not be projected backward into Parts I and II as though it had already been an established property of the vortex cells.

In Part III Maxwell argues that the model now requires it.

He writes:

“I have not attempted to explain this tangential action, but it is necessary to suppose, in order to account for the transmission of rotation from the exterior to the interior parts of each cell, that the substance in the cells possesses elasticity of figure...”

This sentence adds another dated hedge to the record.

“I have not attempted to explain...”

And then another required supposition.

The mechanism is growing.

Light appears as plausibility

The optical connection appears immediately.

Maxwell continues:

“The undulatory theory of light requires us to admit this kind of elasticity in the luminiferous medium, in order to account for transverse vibrations. We need not then be surprised if the magneto-electric medium possesses the same property.”

This must be calibrated carefully.

Optics is already present as a source of plausibility when elasticity is introduced.

The eventual numerical comparison with the velocity of light has not yet been made.

So we should neither remove optics from this stage nor make the later numerical result its hidden premise.

The connection is suggestive before it becomes quantitative.

The medium is itself dielectric

A modern reader can easily hear dielectric and think only of glass, resin, oil or some other ordinary insulating substance placed between conductors.

That is too narrow for Maxwell's Part III.

The vortex medium itself fills the space.

Its cellular substance possesses elasticity.

Electrical displacement therefore belongs not only to ordinary material dielectrics but to the electromagnetic medium occupying the region between bodies.

That point becomes essential when Maxwell later connects this medium with light.

There is no empty modern vacuum in the mechanical construction.

The intervening region is physically filled.

From displacement to current

Maxwell then makes the mathematical move.

He has already connected electromotive force and electrical displacement.

He differentiates that relation with respect to time.

Then he states:

“But a variation of displacement is equivalent to a current, and this current must be taken into account in equations (9)...”

The varying displacement therefore enters the equations relating current and magnetic force.

That is what the 1862 text supports.

It does not yet mean that Maxwell derives the propagation velocity from electric and magnetic changes continually generating one another.

That later route belongs to A Dynamical Theory of the Electromagnetic Field.

Here the displacement term modifies the electromagnetic equations, but the propagation calculation that follows remains mechanical.

Continuity comes afterward

Only after modifying the current equations does Maxwell introduce the continuity equation.

That order is historically important.

The modern pedagogical route often reverses it:

continuity appears first,

a problem appears,

displacement current repairs the problem.

Maxwell's paper proceeds differently.

Dielectric polarisation and displacement come first.

Changing displacement is treated as current.

The current equations are altered.

Then continuity is written.

Charge conservation belongs to the resulting structure.

It is not the documented origin of the displacement concept.

Energy in displacement

The elastic picture also supplies a location for recoverable electrical energy.

Maxwell explicitly writes of:

“The energy in the medium arising from the electric displacements...”

Again the medium matters.

Electrical energy is being assigned to a physical state distributed through space.

We should not replace Maxwell's expression with a modern field-energy formula.

But the conceptual shift is already visible.

The intervening medium can carry energy.

Conductor and dielectric

The contrast can now be stated cleanly.

In a conductor:

electromotive force produces continuing transport;

resistance dissipates energy.

In a dielectric:

electromotive force produces displacement;

the medium responds elastically;

energy can be stored;

a changing displacement contributes as current.

Different material responses are being brought into one electromagnetic framework.

A mechanical route to propagation

Now comes the point that must remain distinct from 1865.

In 1862 the propagation velocity is a property of the mechanical elastic medium.

Maxwell considers transverse vibrations through the elastic substance of which the cells are composed.

The relevant velocity depends on the transverse elasticity of that substance and its density.

In modern-looking shorthand, it has the form of the familiar mechanical relation:

velocity equals the square root of elasticity divided by density.

That is the route.

The cells possess inertia.

They possess elasticity of figure.

Therefore transverse disturbances can travel through them.

The velocity is mechanically determined.

It is not yet derived from a reciprocal cycle in which changing electric and magnetic fields sustain one another.

That second route belongs later.

Two routes must remain separate

The distinction will become central in Chapter II.

1862:

a transverse elastic wave travels through a mechanical vortex medium.

1864–65:

Maxwell reorganises the theory and derives wave propagation from electromagnetic equations after the detailed vortex machinery has been set aside.

Both routes lead toward electromagnetic light.

They are not the same argument.

If we merge them, we erase one of the most important transformations in Maxwell's work.

What did displacement actually survive as?

The survival story is subtler than saying that Maxwell's molecular displacement vanished while a mathematical term survived.

Part of the molecular picture did survive.

For ordinary material dielectrics, later electron theory would represent polarisation through the displacement of bound electrical charges within matter.

A changing polarisation corresponds to a real bound-charge current.

Maxwell's picture of opposite electrical states appearing on different sides of a molecular unit is therefore not simply the part modern physics discarded most completely.

It was transformed.

What changed more radically

The more radical transformation concerns empty space.

In Maxwell's 1862 construction, the electromagnetic medium fills the region between bodies.

It behaves as a dielectric.

It possesses elasticity.

Its displacement is therefore displacement of something.

Later electrodynamics retains the corresponding mathematical structure in vacuum after the mechanical ether loses its physical role.

The modern vacuum term does not require microscopic electrical matter to be displaced through an elastic medium.

That is the deeper change.

The relation survives after its original mechanical referent disappears.

The detailed history of that transformation belongs to Chapter 17.

For now we need only record the distinction.

The survival ledger

The inventory should therefore read:

Ordinary matter:

Molecular polarisation survives in transformed form in later microscopic theories of dielectrics.

Empty space:

The displacement term survives after the mechanical dielectric medium that originally supplied its physical carrier is abandoned.

Mathematics:

A time-varying electric displacement continues to contribute to the electromagnetic equations.

What survives is not identical to what Maxwell originally imagined.

But neither is it merely a symbol with every physical relation removed.

What the model was required to do

The vortex construction was required to reproduce known electromagnetic relations.

It had to accommodate dielectric behaviour.

It had to represent magnetic stress.

It had to incorporate current.

It had to make room for Faraday's polarisation.

Those are documentary constraints visible in the paper.

That is as far as we need to go here.

Faraday remains inside the construction

The connection with Faraday is not rhetorical.

Maxwell's discussion of dielectric polarisation belongs to the line of research Faraday had developed.

But even here we must distinguish ancestry from identity.

Faraday supplied the physical conception of dielectric participation and polarisation.

Maxwell embeds that conception inside a new mathematical and mechanical structure.

The result is not simply Faraday translated into equations.

The representation changes what can be done.

A coefficient depending on the dielectric

Maxwell's relation includes a coefficient depending on the nature of the dielectric.

That is the safest historical formulation at this stage.

Later reconstruction can connect this quantity with the development of dielectric constants and Faraday's specific inductive capacity.

The later genealogy should not be inserted into Maxwell's own terminology.

The paper itself tells us what we need here:

different dielectrics possess different electrical responses.

Those differences enter the equations.

The model becomes capable of waves

Once the cells possess inertia and elasticity of figure, the medium can support transverse vibrations.

That is the mechanical fact needed for the next step.

The velocity of those vibrations can be calculated from mechanical properties of the cell substance.

Then Maxwell connects those properties with electromagnetic quantities.

And only then does a remarkable numerical comparison become possible.

The electrical number

Nineteenth-century electrical measurement used more than one system of units.

A relation between electrostatic and electromagnetic measures produced a quantity with the dimensions of velocity.

The history of that quantity is technically delicate.

Weber and Kohlrausch measured Weber's electrodynamic constant.

That constant is not simply identical to the ratio Maxwell later uses: a factor of $\sqrt{2}$ enters the conversion.

The distinction is easy to lose in modern retellings.

It will be handled explicitly in Chapter 10.

For the present chapter, all that matters is that electrical measurement supplied a numerical quantity that could be connected with the mechanical wave velocity of Maxwell's medium.

The number has not yet spoken

Maxwell will calculate a velocity of approximately

310,740,000,000 millimetres per second.

He will compare it with a value for the velocity of light derived from Fizeau's measurements.

The numbers will be strikingly close.

But agreement does not interpret itself.

Before we quote Maxwell's inference, Chapter 10 has to reconstruct:

what Weber and Kohlrausch actually measured;

why a factor of $\sqrt{2}$ matters;

what Kirchhoff's 1857 work on signals in wires did and did not show;

what optical velocity measurements were available;

and what Maxwell was entitled to conclude from the comparison.

Only then should the famous inference appear.

What Chapter 9 establishes

The route so far is:

Faraday's dielectric induction,

polarisation,

electrical displacement,

elastic response,

changing displacement counted as current,

elasticity of the cell substance,
transverse mechanical vibration.

That is the 1862 sequence.

It is not a modern textbook derivation.

And it is not yet the 1865 field-equation derivation.

Keeping those three stories separate is essential.

What survives and what changes

The machinery of Part III will not survive intact.

The cells disappear.

The idle wheels disappear.

The universal mechanical dielectric disappears.

But the history is not a simple case of mechanism discarded and mathematics preserved.

Molecular polarisation in ordinary matter survives in transformed microscopic theories.

Displacement in empty space survives mathematically while losing the mechanical carrier Maxwell assigned to it.

And the wave calculation itself will soon be reconstructed by Maxwell through a different theoretical route.

The survival is selective.

And transformed.

The next question

The elastic medium now supports a transverse disturbance.

Its velocity can be calculated.

Electrical measurement supplies a number with the same dimensions.

Optics supplies another.

Maxwell is about to put them beside one another.

The comparison is often narrated as if the numbers instantly revealed the nature of light.

They did not.

A number has meaning only inside an argument.

So the next chapter will ask not merely whether the numbers agreed.

It will ask:

What had to be true before their agreement counted as evidence?

Chapter 10

The Velocity

A number is not a theory.

Two numbers that nearly agree are not a theory either.

Their agreement becomes scientific evidence only when there is a reason they should be connected.

In 1861 James Clerk Maxwell obtained a number from electricity and magnetism.

He compared it with a number attributed to the velocity of light.

The agreement, as he reported it then, was almost exact.

A few months later, in print, the numbers were different.

Three years later, they were different again.

The conclusion survived.

The numerical story changed.

That sequence matters.

Two systems for measuring electricity

Nineteenth-century electrical measurement possessed a complication modern notation tends to hide.

Electrical quantities could be defined through different physical effects.

One system was based on electrostatic forces.

Another was based on magnetic effects associated with currents.

The numerical relation between the systems therefore had to be determined experimentally.

And that relation carried the dimensions of a velocity.

That fact alone did not identify it with light.

It merely made such a comparison dimensionally possible.

Weber and Kohlrausch

Wilhelm Weber and Rudolf Kohlrausch performed the crucial electrical comparison in 1856.

They determined an electrodynamic constant connecting electrical quantities measured in different ways.

The historical unit conventions are treacherous.

Weber's electrodynamic current unit and the electromagnetic current unit later used by Maxwell differ by a factor of $\sqrt{2}$.

Maxwell himself later states in the Treatise that the electromagnetic unit of current exceeds the electrodynamic unit in the ratio $\sqrt{2}$ to 1.

After the relevant conversion, the velocity Maxwell used was:

310,740,000 metres per second.

This is the figure he later printed.

Weber and Kohlrausch had not measured light.

They had measured an electrical constant.

Before Maxwell: Kirchhoff

Maxwell was not the first physicist to encounter a light-like velocity in an electrical calculation.

In 1857 Gustav Kirchhoff analysed propagation in conducting wires within an electrodynamic framework associated with Weber.

For a limiting case, he obtained a propagation velocity “very nearly equal” to the velocity of light.

The numerical velocity was likewise Weber's constant divided by $\sqrt{2}$.

This is an important comparison.

But it is not Maxwell's theory.

Kirchhoff was analysing electrical disturbances in conductors.

Maxwell's 1862 result concerns transverse mechanical waves in an elastic electromagnetic medium.

The equality of scale does not erase the difference in physical architecture.

Whether Maxwell knew Kirchhoff's result while making his 1861 inference remains unverified.

The historical landscape contains the result.

Maxwell's documented awareness does not yet.

Maxwell's route in 1861–62

Maxwell's own route remained mechanical.

In Part III of *On Physical Lines of Force*, his medium possesses density and elasticity of figure.

A transverse disturbance can therefore propagate through it with a velocity determined by those mechanical properties.

Electromagnetic quantities determine the relevant parameters.

The result is a velocity derived from electrical and magnetic measurements.

In the printed paper Maxwell gives:

310,740,000,000 millimetres per second

or

193,088 miles per second.

The calculation does not yet come from electric and magnetic fields regenerating one another.

That belongs to 1864–65.

In 1862 the wave is still a transverse vibration of an elastic mechanical medium.

The letter of 19 October 1861

The most valuable evidence comes before publication.

On 19 October 1861 Maxwell wrote to Faraday.

The letter is contemporaneous with the work and survives in manuscript transmission.

Maxwell opens by saying that the conception he had developed had led, when worked out mathematically, to:

| “some very interesting results, capable of testing my theory”

and to numerical relations among optical, electrical and electromagnetic phenomena.

That wording matters.

The comparison is a test in Maxwell’s own language.

But the test is not free of assumptions.

The assumption enters before the comparison

Maxwell tells Faraday that from Weber and Kohlrausch’s determination he had calculated the elasticity of the medium in air.

Then he adds an explicit assumption:

he assumes that this elasticity is the same as that of the luminiferous ether.

Under that assumption he calculates the velocity of transverse vibrations.

So the sequence in the letter is not:

calculation,

comparison,

identity.

It is:

hypothesis about the medium,

calculation under that hypothesis,

comparison with an optical number,

strengthening of belief in the hypothesis.

The comparison tests a construction that already contains the identification as an assumption.

193,088 and 193,118

Maxwell gives his electromagnetic result:

193,088 miles per second.

Then he writes:

“Fizeau has determined the velocity of light = 193118 miles per second, by direct experiment.”

As presented in the letter, the difference is only about thirty miles per second in roughly 193,000.

Approximately 0.016 percent.

Then comes the famous sentence:

“This coincidence is not merely numerical.”

Read in its documentary context, the phrase follows an apparently extraordinary numerical match.

But the optical number was not Fizeau’s published number

Here the history becomes more complicated.

The figure Maxwell quoted in the letter did not come directly from Fizeau’s original paper.

Historical reconstruction indicates that Maxwell found 193,118 miles per second in a handbook by J. A. Galbraith and Samuel Haughton, where it was attributed to Fizeau.

Fizeau’s own published value was different.

Converted appropriately, it was about:

195,937 miles per second.

That changes the evidentiary texture of the episode.

The almost exact agreement in Maxwell's letter depended on the optical number he happened to have before him.

The underlying optical measurement did not agree quite so perfectly.

Before seeing Weber's number

Maxwell adds another important piece of evidence.

He tells Faraday that he had worked out the formulae in the country before seeing Weber's number.

This establishes something real but limited.

By Maxwell's account, the formulae preceded his seeing Weber's number.

That makes the comparison independent of Weber's exact number in that sense.

It does not establish that Maxwell had no prior idea of its approximate magnitude.

Weber and Kohlrausch had themselves discussed the closeness of their electrical constant to the optical velocity according to one historical account, while other scholarship disputes how they interpreted it.

Kirchhoff had already obtained a light-like propagation velocity in 1857.

Whether Maxwell knew either fact at the relevant moment remains open.

The awareness rule therefore applies.

| "Whether my theory is a fact or not"

The letter contains one of Maxwell's strongest methodological qualifications.

After the comparison he says that there is now:

| "strong reason to believe"

that the luminiferous and electromagnetic media are one,

| "whether my theory is a fact or not."

This is not modest decoration.

It separates two questions.

Is the detailed theory literally true?

And:

Has the calculation exposed a relation worth believing?

Maxwell answers them at different levels.

The first stage: October 1861

The first documented stage is therefore:

Electrical value: 193,088 miles/s.

Optical value Maxwell had before him: 193,118 miles/s.

Apparent gap: about 0.016%.

Source of optical number: a handbook attribution to Fizeau, not Fizeau's original published value.

Maxwell's interpretation: strong evidence for identifying the luminiferous and electromagnetic media, while withholding full commitment to the detailed theory.

That is the historical 1861 episode.

It must not be merged with the printed paper.

The second stage: January 1862

When Part III of *On Physical Lines of Force* appeared, Maxwell printed a different optical number.

He gave Fizeau's velocity as:

70,843 leagues per second

and converted it to:

314,858,000,000 millimetres per second

or

195,647 miles per second.

But the number itself contained a transcription error.

Fizeau's published figure was 70,948 leagues, not 70,843.

The printed comparison therefore differs from both the original Fizeau result and the handbook value Maxwell had quoted to Faraday.

The electromagnetic velocity remains:

310,740,000 metres per second.

The gap is now about 1.3 percent.

“Agrees so exactly”

Despite that larger difference, Maxwell writes in the published paper:

“The velocity of transverse undulations in our hypothetical medium, calculated from the electro-magnetic experiments of MM. Kohlrausch and Weber, agrees so exactly with the velocity of light calculated from the optical experiments of M. Fizeau, that we can scarcely avoid the inference that light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena.”

The full sentence matters.

“Agrees so exactly” is Maxwell's judgement.

“We can scarcely avoid the inference” is Maxwell's conclusion.

The numerical agreement is less exact than in the private letter.

The conclusion survives.

The second stage is not the first

This gives us a valuable anti-hindsight lesson.

There was no single immutable numerical coincidence.

The optical number changed between letter and paper.

The published value contained a transcription slip.

Yet Maxwell continued to regard the agreement as physically significant.

That tells us more about the structure of his argument than a polished story of exact equality would.

Weber and Kohlrausch as another control

The electrical constant itself had already invited comparison with light.

According to one historical reconstruction, Weber and Kohlrausch noticed the numerical proximity but denied that it had physical significance.

The historiography is divided on how explicit that comparison was.

What matters here is the broader point.

A numerical proximity can exist without carrying the same theoretical interpretation.

Maxwell's contribution was not merely to notice two similar numbers.

It was to connect the electrical quantity with a transverse wave velocity in the medium he identified with the luminiferous ether.

That is the narrower novelty.

Kirchhoff again

Kirchhoff reinforces the same point.

He had already found a light-scale electrical propagation velocity.

But his result belonged to propagation in conductors.

Maxwell's result belonged to a transverse vibration through an electromagnetic medium identified with the luminiferous medium.

The numbers alone do not define the theoretical meaning.

The surrounding model does.

What was actually tested?

The October letter says the results are capable of testing Maxwell's theory.

What, exactly, is being tested?

Not every part of the vortex mechanism.

Not the idle wheels.

Not the size of the vortices.

Not an arbitrary convention about rotational direction.

The comparison tests whether electrical quantities within Maxwell's construction produce the same propagation scale as optical waves.

That is a more structural test.

And Maxwell's own phrase "whether my theory is a fact or not" shows that he did not equate success in that comparison with verification of every mechanical detail.

The third stage: 1865

By 1865 the evidentiary situation changes again.

In *A Dynamical Theory of the Electromagnetic Field*, Maxwell prints several velocity estimates together.

For the electromagnetic value he gives:

310,740,000 metres per second.

For Fizeau:

314,858,000 metres per second.

Then he gives what he calls the more accurate experiments of Foucault:

298,000,000 metres per second.

And he also includes a value from astronomical aberration:

308,000,000 metres per second.

The numerical picture is now visibly broader.

Foucault widens the gap

Foucault's improved optical determination does not move the optical value closer to Maxwell's electrical value.

It moves it farther away.

310.74 million versus 298 million metres per second gives a discrepancy of roughly 4 percent.

Maxwell prints both numbers himself.

That fact is essential.

By 1865 the electromagnetic theory of light no longer rested rhetorically on an almost exact numerical identity like the one presented in the 1861 letter. The second derivation, from the field equations, supplied another route. Maxwell now wrote that “the velocity of light deduced from experiment agrees sufficiently well with the value of v deduced from the only set of experiments we as yet possess.”

Three stages of evidence

The chronology can now be summarised.

October 1861

193,088 versus 193,118 miles/s.

Near-exact apparent agreement.

Optical number from a handbook attribution.

The identity of the two media enters as an assumption and is strengthened by the comparison.

January 1862

310.74 versus 314.858 million m/s.

About 1.3 percent difference.

The optical figure contains Maxwell’s transcription slip.

Maxwell nevertheless writes “agrees so exactly”.

1865

310.74 versus Foucault’s 298 million m/s, with other optical estimates also listed.

The gap can be several percent.

The electromagnetic theory of light remains.

The evidentiary structure has changed.

Evidence does not remain frozen

This is scientifically more interesting than a single miraculous equality.

An initial argument can survive while one of its supporting numbers changes.

But it survives only if additional relations, experiments or theoretical structures give it support.

The strength of Maxwell's theory by 1865 cannot therefore be reduced to the quality of the 1861 numerical match.

The theory itself has been rebuilt.

Foucault is later evidence

Chronology remains essential.

Foucault's 1862 result did not lead Maxwell to his October 1861 inference.

It came afterward.

Nor should Foucault be used merely as a more accurate confirmation.

Numerically it weakened the original closeness.

Its significance lies in the evolving experimental landscape.

The electrical number would change too

The electromagnetic side was not a final constant delivered once and forever by Weber and Kohlrausch.

The ratio of electrical units would later be measured again with improved methods.

That history belongs with Maxwell's metrological work and will be treated later.

The equality between electromagnetic and optical propagation did not become more credible because the original 1850s measurements happened to be perfect.

They were not.

It became more credible because theory, measurement and experimental electromagnetic waves increasingly converged.

Faraday's earlier possibility

Faraday had already speculated in 1846, in *Thoughts on Ray-Vibrations*, about propagation associated with lines of force.

Maxwell explicitly acknowledged that work in 1865.

But the awareness rule must still be respected for 1861.

The fact that Maxwell later knew and cited Faraday's 1846 paper does not, by itself, prove precisely when or how it entered the 1861 reasoning.

Later acknowledgement is not contemporaneous process evidence.

The landscape belongs to the historian

Weber and Kohlrausch.

Kirchhoff.

Faraday.

Thomson.

Fizeau.

These are all genuine parts of the historical landscape.

But we must distinguish that landscape from what Maxwell demonstrably had in hand at one particular moment.

For October 1861 we directly know about Weber's number and the optical figure from the handbook because Maxwell says so.

Other possible inputs remain subject to the awareness rule.

No Eureka is required

Nothing in this episode requires us to invent a flash of recognition.

The letter gives us something better.

A stated conception.

A mathematical development.

An assumption.

A numerical test.

A comparison.

A strengthened belief.

Those are documentary acts.

They are enough.

A test without a clean victory

The velocity comparison is therefore both stronger and weaker than the legend.

Stronger, because the mathematical relation was sufficiently structured for Maxwell to regard the numerical result as a genuine test.

Weaker, because the famous agreement changed substantially depending on which optical value was used.

The first near-perfect match relied on a handbook value.

The published paper contained a numerical transcription error.

The better Foucault measurement widened the discrepancy.

And Maxwell's theory survived all three stages.

What actually survived?

Not the exact 1861 equality.

Not the precise optical number.

Not every mechanical component.

What survived was the relation:

the characteristic electromagnetic propagation velocity is the velocity of light.

Then, in 1864–65, Maxwell would derive the wave through a different theoretical route.

That is a much stronger foundation than any one numerical coincidence.

The hedge series grows

The velocity episode also adds to the documentary sequence of Maxwell's qualifications.

1855:

an imaginary fluid not offered as a hypothetical substance.

1860:

an elastic-sphere system whose correspondence with gases remained to be established.

1861:

idle-wheel machinery explicitly provisional and temporary.

October 1861:

| “whether my theory is a fact or not.”

1862:

dielectric relations independent of a theory of internal mechanism.

1862:

| “I have not attempted to explain this tangential action.”

This is now a substantial documentary pattern.

The Epilogue will have to compare it against Thomson, Rankine and others before deciding what, if anything, was distinctively Maxwellian.

A conclusion that outlives its first evidence

The electromagnetic theory of light did not remain tied to the exact numerical circumstances in which Maxwell first announced it to Faraday.

That is one of the deepest lessons of the episode.

The 1861 comparison helped Maxwell strengthen a hypothesis.

The 1862 paper published the inference.

The 1865 theory reorganised the mathematics and displayed a less perfect numerical landscape.

The conclusion survived because the network of reasons supporting it expanded.

What happens next

The detailed vortex mechanism had helped Maxwell obtain the first electromagnetic light result.

But by 1865 the theory would no longer require that machinery in the same way.

This gives us the next test.

If the electromagnetic wave survives when the microscopic mechanism is removed, which part of the theory was actually carrying the result?

That question leads directly to Chapter II.

Chapter II

A Dynamical Theory Without the Vortex Machinery

In 1865 Maxwell published a theory of the electromagnetic field that looked different from the mechanism of 1861–62.

The difference is easy to exaggerate.

The molecular vortices and their intermediate particles no longer organise the derivation.

But the electromagnetic field has not become an immaterial modern field.

Maxwell still assumes a medium.

He still speaks of energy in that medium.

And he calls the theory dynamical for a specific reason:

“because it assumes that in that space there is matter in motion.”

The transition is therefore not from mechanism to pure mathematics.

It is from one highly specified mechanical construction to a more general dynamical theory in which the detailed internal motion is left unspecified.

A paper written in 1864, published in 1865

On a Dynamical Theory of the Electromagnetic Field was received by the Royal Society on 27 October 1864 and read on 8 December.

The printed paper appeared in 1865.

Those dates matter because the electromagnetic argument was already changing while Maxwell was still working within the programme opened by *On Physical Lines of Force*.

The later paper is not a retrospective summary written after the mechanical theory had disappeared.

It is the next stage of the same research programme.

The field is a region of physical action

Maxwell defines the electromagnetic field as the part of space in the neighbourhood of electrified or magnetic bodies in which electromagnetic phenomena may occur.

This sounds familiar to a modern reader.

But the physical content attached to the word is different.

He explicitly writes of:

| “an ethereal medium filling space and permeating bodies”.

The field is not being substituted for every medium.

It describes the state of a region in which a medium is still physically involved.

Why call it dynamical?

Read together with Maxwell’s explanation of the word *dynamical* in §3, the paper treats motion and energy as belonging to the physical system represented.

In his field theory, they do.

He develops the theory using kinetic and potential energy.

This is not decorative language added to equations after the fact.

The dynamics is part of the architecture.

The field is something in which energy can be stored and through which dynamical relations can be formulated.

The action-at-a-distance alternative

Maxwell begins against a real competitor.

He discusses theories associated with Weber and C. Neumann, describing them as:

| “exceedingly ingenious, and wonderfully comprehensive”.

That wording matters.

The competing programme is not dismissed as primitive.

It is powerful.

Its attraction lies partly in its ability to express electromagnetic interactions mathematically without constructing an intervening mechanical medium.

Maxwell’s objection is not that it lacks mathematical sophistication.

He points instead to the mechanical difficulties involved in particles acting at a distance with forces dependent on their velocities.

His own theory takes another route.

Locality still needs a medium

Maxwell’s preference for a field description does not yet mean that interaction occurs in empty geometric space with no physical carrier.

The medium supplies the locality.

Energy and stress belong to the intervening region.

Changes propagate through it.

That is why the word *field* must be read historically.

The physical commitment has changed relative to the vortex model, but it has not vanished.

The most important paragraph: §73

Maxwell himself tells us how the status of the mechanism has changed.

In Part III, §73, he recalls that in the earlier paper he had attempted to account for electromagnetic action by assuming:

| “a particular kind of motion and a particular kind of strain”.

Then he states what he is doing now:

| “In the present paper I avoid any hypothesis of this kind”.

That is more precise than saying that he simply abandoned mechanics.

He does not avoid dynamics.

He avoids specifying that particular internal mechanical mechanism.

Then comes the decisive qualification.

Maxwell says that expressions such as electric momentum and electric elasticity are to be considered:

| “illustrative, not as explanatory.”

The sentence gives the book one of its clearest examples of graded commitment.

What remains physically committed?

The same paper that makes those expressions illustrative still says that the theory is dynamical because matter is in motion.

So two levels of commitment coexist.

At one level, Maxwell remains committed to a physical medium carrying dynamical state.

At another, the particular mechanical vocabulary used to represent that state is explicitly illustrative rather than explanatory.

The difference should not be blurred.

From actual mechanism to general dynamics

The 1861–62 vortex theory supplied a literal-looking internal architecture:

rotating cells,

elastic distortion,

intermediate particles,

and a mechanical route to electromagnetic effects.

The 1865 theory no longer requires those components.

Instead Maxwell organises the subject through energy and the dynamics of connected systems.

The field is treated as a dynamical system without specifying the detailed molecular mechanism underneath it.

This is a reduction of mechanical specificity.

It is not a retreat from physical realism altogether.

Twenty variables, twenty equations

The mature-looking compactness of the four equations taught today is absent.

Maxwell's own presentation contains twenty quantities and twenty equations arranged in groups.

That complexity is historically important.

The theory later called "Maxwell's equations" would be reorganised substantially by Heaviside, Gibbs, Hertz and others.

Maxwell's 1865 theory is already powerful, but it does not yet possess the visual form through which twentieth-century students usually encounter it.

The second route to waves

In 1862 the velocity of electromagnetic disturbance emerged as a mechanical property of the elastic medium composing the cells.

The 1865 paper reaches propagation by another route.

Maxwell takes the general field equations and considers a non-conducting region.

From those equations he derives a transverse disturbance propagating with a definite velocity.

The detailed gears are no longer doing the derivation.

The wave is now embedded in a more general field theory.

This is the second electromagnetic route in the book.

Keeping it separate from 1862 is essential.

The comparison with light returns

The velocity again becomes comparable with optical measurements.

Maxwell does not say that the numerical agreement is exact.

He writes:

“Hence the velocity of light deduced from experiment agrees sufficiently well with the value of v deduced from the only set of experiments we as yet possess.”

The final clause matters because the electrical evidence itself would later be measured again.

Then he states the stronger physical conclusion:

“light is an electromagnetic disturbance propagated through the field according to electromagnetic laws.”

The difference between those two sentences matters.

The numerical evidence is approximate.

The theoretical identification is strong.

A stronger theory with less perfect numbers

This creates a useful historical reversal.

The private 1861 letter had presented a spectacularly close numerical coincidence.

The 1862 paper still described the agreement as so exact that the inference seemed nearly unavoidable.

By 1865 the measurements were visibly spread.

Yet Maxwell's theoretical claim about light had become more explicit.

Confidence was no longer resting on one dramatic numerical near-equality.

It was being carried by a larger theoretical structure.

Faraday's ray vibrations

Maxwell also acknowledges a predecessor who should not be erased from this history.

In Part I, §20, he refers to Faraday's 1846 *Thoughts on Ray-Vibrations*.

Faraday had speculated that the propagation of light might be associated with lines of force.

Maxwell says Faraday's theory is:

| “the same in substance”

as the theory he has begun to develop in the paper, except that in 1846 there were no data from which the velocity of propagation could be calculated.

That acknowledgement belongs to 1865.

It does not prove what Maxwell knew about the paper in 1861.

The awareness question must remain dated.

What has become independent of mechanism?

Not everything.

The existence of a medium remains physical.

Energy in the field remains physical.

Matter in motion remains physical.

What has become less dependent on detailed mechanism is the mathematical structure connecting electromagnetic quantities.

The theory can derive propagation without requiring the reader to accept molecular vortices and idle wheels.

That is a real change in representational architecture.

A theory can become more general by saying less

The 1865 paper is in one sense less pictorial than the 1861–62 theory.

It specifies less about the microscopic constitution of the medium.

Yet it is more general.

That combination is one of the recurring themes of Maxwell's work.

Removing details can increase reach when those details are not carrying the relations that matter.

The theory becomes less tied to one possible mechanism while preserving the dynamical structure needed for electromagnetic phenomena.

But the mechanism has not simply died

The later history prevents an overclean narrative.

Maxwell continued to discuss mechanical explanations after 1865.

The *Treatise* returned to the hypothesis of molecular vortices when discussing the magnetic rotation of light.

So §73 should not be read as a permanent renunciation of mechanical hypotheses.

Its wording is narrower:

in the present paper he avoids a hypothesis of that kind.

The precision strengthens rather than weakens the historical argument.

What Chapter II establishes

The transition from 1862 to 1865 is not:

mechanical fantasy , true field theory.

It is:

specified mechanism , more general dynamical field theory,

with the physical medium retained,

the detailed mechanism no longer required for the derivation,

and the status of certain mechanical expressions explicitly downgraded to illustration rather than explanation.

That is a more complicated transition.

It is also more revealing.

The next question is unavoidable.

If equations can survive while mechanisms change, how much of the machinery must a physicist believe is real?

Chapter 12

How Much of the Machinery Must Be Real?

Maxwell's electromagnetic work between 1855 and 1865 does not display one fixed relation between mathematics and mechanism.

It displays several.

An imaginary fluid can be openly nonliteral.

An electrotonic quantity can function as artificial notation before its physical nature is clear.

A temporary theory can guide experiment.

A molecular vortex mechanism can be developed in extraordinary detail.

One part of that mechanism can be offered as mechanically conceivable while Maxwell says he would not willingly assent to it as an electrical hypothesis.

And in 1865 a detailed mechanical hypothesis can be avoided while the theory remains dynamical and physically committed to matter in motion.

This is not inconsistency in the trivial sense.

It is a layered architecture of commitment.

Ten years, several statuses

The sequence spans roughly ten years.

1855–56: the imaginary fluid is “not even a hypothetical fluid” introduced to explain actual phenomena.

1855–56: the electrotonic representation “involves no physical theory” and is “only a kind of artificial notation”.

1855–56: temporary theory is defended because it can guide experiment without impeding a later true theory.

1861: the idle-wheel connexion is mechanically conceivable, but Maxwell says he would not willingly assent to it as an electrical hypothesis.

1862: the relation between electromotive force and electric displacement is stated to be independent of any theory of the internal mechanism of dielectrics.

1864–65: Maxwell says that in the present paper he avoids the earlier hypothesis of a particular motion and strain, and that mechanical expressions are “illustrative, not as explanatory”.

A single label such as *model* hides these differences.

What an equation commits us to

The 1865 paper provides a particularly clear case.

Maxwell calls the theory dynamical because:

| “it assumes that in that space there is matter in motion.”

That is a physical commitment.

But in §73 he also says:

| “In the present paper I avoid any hypothesis of this kind”

when referring to the earlier particular motion and strain.

And he says that expressions such as electric momentum and electric elasticity are to be considered:

| “illustrative, not as explanatory.”

So removing the idle wheels does not remove physical commitment.

It redistributes it.

The theory is less committed to a particular microscopic mechanism while remaining committed to a medium, energy and dynamical state.

Not every symbol has the same ontology

This is easy to forget once equations are written in a uniform notation.

A line of mathematics can contain quantities with different physical statuses.

Some may represent directly measurable quantities.

Some may represent inferred states.

Some may be coordinates in a dynamical formalism.

Some may function as analogical language.

The equation alone does not announce which is which.

Historical interpretation therefore requires Maxwell's accompanying prose.

Physical analogy is not one thing

The electromagnetic sequence also shows that "analogy" can do several jobs.

A fluid analogy can transport mathematics without claiming literal fluid substance.

An elastic analogy can make stresses and propagation mechanically intelligible.

A specific vortex construction can provide a worked mechanism.

A term such as electric elasticity can later remain as illustration after the mechanism has been left unspecified.

Calling all of these "analogies" is correct but insufficient.

The differences are epistemic.

A mechanism can be productive before it is secure

The vortex theory produced real theoretical consequences.

It organised magnetic stresses.

It connected dielectric displacement with electromagnetic current.

It yielded a transverse wave velocity.

Its scientific productivity therefore cannot be assessed only by asking whether rotating ether cells existed.

A mechanism may contribute to a successful theory even if the mechanism itself later loses status.

This is not a retrospective excuse for a false picture.

The relations still have to survive independent constraints.

Maxwell's own hedges

The important point is that the qualifications were not invented by later historians to rescue him.

Maxwell supplied many of them himself.

- | “not even a hypothetical fluid”
- | “only a kind of artificial notation”
- | “temporary theory”
- | “would not willingly assent”
- | “independent of any theory about the internal mechanism of dielectrics”
- | “illustrative, not as explanatory”

Taken together, the phrases show repeated differentiation between what a representation can do and how literally it should be read.

But they do not yet establish that this differentiation was uniquely Maxwellian.

Thomson is a control, not a precursor to be surpassed

William Thomson complicates any easy claim of distinctiveness.

In 1847 he described his own construction to Faraday as:

- | “merely a sketch of the mathematical analogy”.

He said he had not ventured to make it the foundation of a physical theory.

Yet he also considered the possibility that such a theory, combined with the undulatory theory of light, might explain the effect of magnetism on polarised light.

So the practice of exploiting a mechanically suggestive representation while withholding full physical commitment predates Maxwell's mature electromagnetic work.

Maxwell is not alone.

Rankine is an even sharper control

William Rankine makes the comparison harder.

In 1855 he argued that:

| “a hypothetical theory is necessary as a preliminary step”

to reduce phenomena to simplicity and order before progress can be made in framing an abstractive theory.

At the same time, Rankine was developing a rich mechanical programme involving molecular vortices.

That is close to the candidate pattern examined in this book:

use a specified hidden mechanism as a working tool,

while refusing to let the certainty of general relations depend completely on the truth of that mechanism.

The similarity must be taken seriously.

Similarity does not settle identity of method

Rankine's case prevents a simple conclusion.

His abstractive programme sought relations whose certainty did not depend on the truth of a mechanical hypothesis, while he continued to work with the hypothesis.

Maxwell's 1865 move is narrower and different: in that paper he explicitly avoids the earlier particular mechanism while retaining a dynamical electromagnetic structure.

Even that difference should not be exaggerated.

Maxwell later returned to molecular-vortex explanation in the *Treatise* when discussing magnetic rotation of light.

The historical record does not give us a neat ladder from mechanism to abstraction.

It gives overlapping strategies.

Ludvig Lorenz: another control

A further caution comes from Ludvig Lorenz.

In 1867 Lorenz developed an independent electromagnetic theory of light, published in *Philosophical Magazine*, fourth series, volume 34, pages 287–301.

It postdates Maxwell's 1865 paper but was developed independently by a different route, using retarded potentials.

That matters because Maxwell's successful identification of light with electromagnetic disturbance does not establish that his particular mechanical or representational route was uniquely necessary.

Different theoretical architectures could approach related relations.

Underdetermination is not defeat

If several representations reproduce important phenomena, physics does not become impossible.

The problem changes.

One asks which relations are robust across representations.

One asks which additional experiments can distinguish the alternatives.

One asks whether a mechanism generates new consequences beyond the relations already shared.

Multiple representations therefore increase the demand for discriminating evidence.

They do not eliminate the possibility of knowledge.

The equations do not choose their own interpretation

Maxwell's 1865 equations constrain electromagnetic phenomena.

They do not, by themselves, tell a later historian how literally every accompanying mechanical expression was meant.

For that, the prose matters.

§3 tells us that the theory assumes matter in motion.

§73 tells us that specified mechanical expressions are illustrative rather than explanatory.

The two statements must be read together.

One without the other distorts the theory.

The modern black box

A modern reader can solve many electromagnetic problems without asking what mechanical substance fills space.

That is a useful retrospective fact.

It is not Maxwell's starting point.

Calling the mature equations a "black box" can therefore be useful only if the metaphor is marked as ours.

Maxwell did not inhabit a conceptual world in which the field equations simply floated free of medium, energy and mechanical questions.

The historical question is how the relations acquired increasing independence from particular mechanical pictures.

What survives a change of picture?

The answer differs by case.

Some vocabulary disappears.

Some mechanisms disappear.

Some relations remain.

Some quantities retain their names but acquire new physical interpretations.

Some later physicists reorganise the equations so thoroughly that the canonical form no longer resembles Maxwell's printed system.

The survival of a relation is therefore not identity of meaning.

It is continuity under transformation.

Poincaré and Duhem: later readers of Maxwell's plurality

The representational plurality that Maxwell left behind became a problem for later physicists and philosophers.

Poincaré emphasised the suggestiveness of Maxwell's multiple routes.

Duhem objected to the contradictions that such plurality could tolerate.

Those responses belong to the afterlife of Maxwell's theory.

They are evidence not for what Maxwell privately intended, but for what later readers found striking in the architecture of his work.

How much machinery must be real?

The historical answer is not a number.

Maxwell's own writings distribute commitment unevenly.

In some places he explicitly denies literal physical status.

In others he constructs a mechanism as a plausible physical account.

In 1865 he retains matter in motion while declining to specify the earlier microscopic mechanism.

So the question cannot be answered by saying either:

none of the machinery mattered, or

the machinery had to be literally true.

Both are too simple.

What the electromagnetic sequence establishes

Between 1855 and 1865 Maxwell repeatedly worked with representations whose scientific usefulness did not map one-to-one onto their literal physical status.

That statement is documentary.

The further claim that this was distinctively Maxwellian is comparative.

Thomson and Rankine already make the strongest version doubtful.

Lorenz shows that related theoretical outcomes could be approached independently.

The final comparative judgement therefore belongs at the end of the book, after the other domains have been examined.

For now, the electromagnetic evidence gives us something more modest and secure:

a theory can do serious scientific work while the ontological status of some of its machinery remains deliberately unsettled.

Chapter 13

When Maxwell's Molecules Failed

A good theory can fail in an informative way.

Maxwell's kinetic theory had already demonstrated this in 1860.

The velocity distribution was powerful.

The elastic-sphere model produced measurable consequences.

And Maxwell published evidence that parts of the construction were already in trouble.

The next years did not simply repair those troubles.

Some experiments vindicated one prediction.

Other measurements pushed the theory toward a new molecular law.

And that new law was itself chosen, by Maxwell's own account, to fit an experimental result that later turned out not to be generally correct.

The history is therefore not a sequence of error followed by correction.

It is more interesting.

Viscosity returns

The density-independence of gaseous viscosity had looked startling in 1860.

Maxwell had explicitly noted that the only experiment known to him did not appear to confirm it.

He returned to the question experimentally.

By 1866 he could report two striking conclusions:

the viscosity was independent of density,

and, according to his measurements, was very nearly proportional to absolute temperature.

The first result supported one of kinetic theory's most surprising predictions.

The second created another problem.

Katherine and the experiment

Katherine Maxwell participated in the experimental work, including maintaining the apparatus under controlled thermal conditions.

What matters here is that the viscosity investigation was experimental work performed within Maxwell's household and laboratory practice, not simply a calculation checked by somebody else.

Density succeeds

The density result is theoretically striking.

Reducing the density of a gas gives fewer molecules to transport momentum.

But it also increases their mean paths between collisions.

Those effects can compensate.

Viscosity can therefore remain nearly independent of density.

By the middle of the 1860s experimental work, including Maxwell's and that of other investigators such as O. E. Meyer, was making this once-startling prediction increasingly credible.

A result that had stood against the only experiment Maxwell knew in 1860 was acquiring evidence.

Temperature fails

The temperature dependence was different.

For hard elastic spheres the theory gave viscosity varying roughly as the square root of absolute temperature.

Maxwell's experiments suggested instead that viscosity was proportional to absolute temperature.

He therefore concluded that the hard-sphere interaction had to be abandoned.

His 1867 statement is unusually explicit:

“The experimental result, that the viscosity is proportional to the absolute temperature, requires us to abandon this hypothesis...”

He then states what must replace it:

“...and to adopt the hypothesis of a repulsive force inversely as the fifth power of the distance between the molecules, which is the only law of force which gives this result.”

That is Maxwell’s stated reason.

The new force law was chosen to reproduce the measured temperature dependence.

The fifth-power law

A repulsive force varying as the inverse fifth power of intermolecular distance had a remarkable mathematical property.

It made important parts of the collision problem tractable.

Transport coefficients could be derived with unusual analytical power.

Particles obeying this interaction later became known as Maxwell molecules.

But tractability was a consequence of the choice.

It was not the reason Maxwell himself gave for making it.

The reason he gave was experimental fit.

The experiment had misled the model

That fit did not remain secure.

By 1893 William Sutherland could look back on the history and write that Maxwell had been led, by inaccurate experiments, to believe that viscosity for natural gases was proportional to absolute temperature.

Later measurements produced temperature exponents varying roughly from 0.7 to 1.0, depending on the gas.

The simple proportionality $\eta \propto T$ was not a universal law.

The historical irony is sharp.

Experiment had forced Maxwell away from hard spheres.

But the experiment also pushed him toward a force law fitted to a relation that was itself not generally correct.

Experiment can constrain in the wrong direction

This complicates a simple philosophy of testing.

We often say that experiment constrains the freedom of invisible models.

It does.

But experiments are measurements, and measurements can be wrong.

A model can therefore be modified in response to evidence that later changes.

That does not make experiment optional.

It means that constraint itself has a history.

What remained valuable

The fifth-power model was not scientifically empty because the temperature relation motivating it was inaccurate.

Its mathematical tractability generated important kinetic results.

It became a highly productive idealised interaction.

A model can therefore acquire value for reasons different from the empirical reason that originally selected it.

Again the layers separate.

Maxwell revises his own derivation

As Chapter 7 noted, the 1867 paper returns to the velocity distribution and to Maxwell's earlier independence assumption, which he now says "may appear precarious".

He gives another route to the distribution.

The distribution remains.

Its justification changes.

Clausius as critic

Clausius had supplied one of the foundations of the theory through mean free paths and collisions.

He also criticised Maxwell's treatment of heat conduction.

Maxwell acknowledges this directly in 1867:

“there were several errors in my theory of conduction of heat in gases which M. Clausius has pointed out in an elaborate memoir on that subject.”

Clausius therefore remains a control, not merely a predecessor left behind after Maxwell enters the story.

The specific-heat problem

A deeper difficulty resisted changes in the collision law.

Classical mechanics suggested that available independent modes of motion should participate in the sharing of energy.

For molecules capable of more than simple translation, this generated predictions for heat capacities.

Observed gases did not cooperate.

Maxwell had already encountered the problem in 1860.

It persisted.

By 1875 he called it:

“the greatest difficulty yet encountered by the molecular theory.”

The phrase is one of the strongest anti-triumphalist statements in his kinetic work.

Boltzmann's alternative suggestion

Boltzmann was among those who tried to understand the difficulty. Maxwell reported Boltzmann's suggestion that the explanation might lie in the mutual action between the molecules and the aetherial medium surrounding them.

That proposal did not provide the later quantum solution.

Its importance here is comparative.

The failure was visible.

Different physicists proposed different mechanisms.

None possessed the twentieth-century answer.

No quantum rescue in advance

Later quantum theory would transform the specific-heat problem by changing the assumptions governing internal degrees of freedom.

That knowledge must not be inserted into Maxwell's reasoning.

For Maxwell, the discrepancy remained unresolved.

He could identify the failure.

He could not know why classical equipartition would ultimately cease to apply in the way expected.

Success and failure coexist

By the late 1860s the kinetic theory therefore contains several layers with different evidentiary fortunes.

The velocity distribution: retained.

Density-independence of viscosity: increasingly supported.

Hard-sphere interaction: abandoned.

Temperature proportionality: provisionally accepted, later weakened.

Inverse-fifth-power law: productive, but tied historically to an inaccurate empirical relation.

Heat conduction treatment: corrected after Clausius's criticism.

Specific heat: unresolved and serious.

No single label, success or failure, captures the theory.

A theory can be wrong for productive reasons

The most important lesson is not that Maxwell made mistakes.

Every scientist does.

It is that a mistaken empirical constraint could generate a model that remained mathematically productive.

That fact complicates retrospective narratives of scientific rationality.

Theories are not always improved by moving monotonically closer to truth at every intermediate step.

Sometimes a wrong measurement redirects a theory into a representation that exposes useful structure anyway.

Selective survival again

The kinetic story now genuinely parallels electromagnetism at one level.

In electromagnetism, detailed vortex machinery disappears while displacement and wave relations survive.

In kinetic theory, the hard-sphere interaction disappears while the distribution survives.

Then a replacement force law acquires its own mixed history.

The parallel is documentary.

Whether Maxwell consciously understood both episodes through one philosophy remains unproved.

What failure teaches

Invisible mechanisms are underdetermined precisely because many mechanisms can reproduce some observed facts.

Experiment removes some possibilities.

Further experiment can reopen them.

A successful invisible theory therefore has to survive not one test but an evolving network of constraints.

Maxwell's kinetic theory did not reach its importance by avoiding failure.

It became important while carrying failure inside it.

Chapter 14

Stability, Governors and Statistical Law

A steam engine can run too fast.

If the load falls while the driving power remains, its speed rises.

A governor detects the change and alters the supply.

The correction may restore the desired motion.

Or it may arrive too late.

It may be too strong.

The system may overshoot.

A second correction may overshoot in the other direction.

A device designed for regulation can itself become a source of oscillation.

In 1868 Maxwell gave this problem a general mathematical form.

Not the first mathematics of governors

He did not begin the subject.

George Biddell Airy had already analysed governor behaviour mathematically in 1840.

And the general algebraic stability questions stimulated by Maxwell's paper would later be pushed further by Edward Routh, whose 1877 Adams Prize work supplied a general stability criterion.

Maxwell belongs inside that development, not outside it.

His contribution was to formulate the regulation problem broadly enough that the stability of the entire dynamical response became the object of analysis.

The governor Maxwell already knew

Governor mechanisms were already part of Maxwell's technical vocabulary.

In On Physical Lines of Force in 1861 he referred to Siemens's governor while explaining idle wheels whose centres could move.

That establishes familiarity.

It does not establish a causal route from electromagnetism to control theory.

Seven years later, regulation itself became the subject.

Nearly uniform

Maxwell begins On Governors by defining a governor as:

“a part of a machine by means of which the velocity of the machine is kept nearly uniform, notwithstanding variations in the driving-power or the resistance.”

The word nearly matters.

The system is allowed to move away from its nominal condition.

The question is what happens afterward.

Feedback, retrospectively

Modern control theory calls the underlying loop feedback.

That is our later term.

The basic structure is nevertheless present:

the machine's state affects the regulator;

the regulator alters the driving action;

the altered action changes the state again.

Whether the loop stabilises the system depends on the dynamics of the whole connexion.

Stability is about response

An equilibrium operating condition is not enough.

A system may possess an equilibrium and still be unusable because small disturbances grow.

The key question is dynamical:

does a deviation decay,

persist,

oscillate,

or increase?

This connects governors structurally with Maxwell's earlier stability work on Saturn.

But structure is not genealogy.

Saturn did not “teach” control theory

Saturn and governors both involve perturbations.

That does not establish that Maxwell transferred one method consciously from one problem to the other.

The documented claim is narrower.

Across distinct domains, Maxwell analysed whether departures from a nominal state diminish or amplify.

That pattern is visible in the mathematics.

No hidden mental bridge is required.

The demon enters before Theory of Heat

On 11 December 1867 Maxwell wrote to Peter Guthrie Tait about a hypothetical being capable of observing and sorting molecules.

In the letter the being is described through extraordinary observational and manipulative powers.

When Maxwell later presented the idea in Theory of Heat in 1871, he described:

“a being whose faculties are so sharpened that he can follow every molecule in its course”.

The word demon was not Maxwell's original label.

William Thomson put “Maxwell’s intelligent demons” into print in 1874.

What the being shows

The thought experiment served to show that conclusions applying reliably to enormous populations of molecules need not operate as mechanically inviolable restrictions on each individual molecule.

A sufficiently discriminating being could sort molecular motions in ways ordinary macroscopic processes cannot.

The point concerns the statistical character of thermodynamic regularity.

It need not be reconstructed as Maxwell’s undocumented private “purpose” beyond what his published treatment supports.

A law of multitudes

The second law therefore differs from an elementary prohibition written into each collision.

Its overwhelming reliability belongs to systems containing immense numbers of particles.

Microscopic mechanical possibilities and macroscopic statistical regularities occupy different descriptive levels.

The distinction is exactly the kind of layered physical reasoning that kinetic theory had made possible.

Boltzmann as control

Boltzmann’s 1868 work extended Maxwell’s velocity distribution and began developing the statistical treatment in directions that would eventually become central to kinetic theory.

He is therefore not merely a later name attached to Maxwell’s distribution.

He is an independent developing voice in the same problem.

The statistical interpretation of macroscopic regularity would become increasingly associated with this Maxwell–Boltzmann line of work, though neither man’s early formulation should be collapsed into the mature twentieth-century framework.

Singular points

Maxwell also reflected directly on the amplification of small causes.

In an Eranus Club essay delivered on 11 February 1873, he discussed what he called singular points.

At such points, influences too small for a finite observer to take into account could produce consequences of great importance.

His examples include the rock loosened by frost and the small spark that ignites a forest.

This is not modern chaos theory.

But it is a documented recognition that predictability can fail dramatically near sensitive configurations even when physical laws themselves remain intact.

Determinism and practical knowledge

A deterministic equation does not automatically yield practical predictability.

Prediction also depends on sensitivity to initial conditions, stability and the precision with which relevant variables can be known.

Maxwell did not formulate twentieth-century nonlinear dynamics.

But he had identified a logical gap between lawful evolution and reliable finite prediction.

Three stability problems

We can now place three episodes beside one another.

Saturn:

Which possible constitutions survive perturbation?

Governors:

Which regulating systems suppress deviations instead of amplifying them?

Statistical physics:

Which macroscopic regularities remain reliable despite uncontrolled microscopic motions?

The problems are not identical.

Their mathematical languages differ.

But each asks what remains stable when the system is disturbed.

A cross-domain thread, not a hidden programme

This recurrence is strong enough to be analytically useful.

It does not establish a single private Maxwellian method.

Airy, Routh, Clausius and Boltzmann ensure that the comparison class remains visible.

The defensible conclusion is narrower:

Maxwell repeatedly worked on physical systems in which response to disturbance carried more information than the ideal state alone.

Stability changes what has to be known

One need not know every detail of a system to know whether disturbances decay.

One need not track every molecule to know a statistical distribution.

One need not reconstruct every moment of a governor's mechanism to derive a stability condition.

System-level relations can therefore support prediction even when microscopic knowledge is incomplete.

That is not an argument against mechanism.

It is an argument about levels of description.

Toward measurement

A governor requires a measurable deviation.

A gas theory requires measurable macroscopic quantities.

An electromagnetic theory requires reproducible units.

The next chapter turns to the infrastructure that allows those comparisons to become quantitative.

Measurement is not merely where theory is checked.

It helps determine what the theory can mean.

Chapter 15

Measurement as Theory

A number does not become physical merely because an instrument displays it.

It needs a unit.

The unit requires a definition.

The definition requires a reproducible operation.

And quantities measured by different physical methods can only be compared if the system preserving those relations is understood.

For Maxwell, electrical measurement was not bookkeeping added after theory.

It belonged to the theoretical architecture.

The British Association committee

The British Association committee on electrical standards was formed at Manchester in September 1861.

Maxwell joined it in 1862.

The immediate problem was practical as well as scientific.

Telegraph networks required resistance measurements that could be reproduced across laboratories and engineering systems.

A resistance standard had to be more than a local apparatus whose number happened to be known.

It had to belong to a coherent system of measurement.

The London work

In 1863 a London subcommittee including Fleeming Jenkin, Maxwell and Balfour Stewart carried out resistance-standard work at King's College.

Charles Hockin subsequently replaced Stewart in part of the experimental programme.

Coils had to be rotated.

Galvanometers calibrated.

Temperatures controlled.

Contacts understood.

Reproducible electrical units were made through coordinated theoretical and experimental labour.

Absolute measurement

The larger ambition was to relate electrical quantities to mechanical standards involving length, mass and time.

This encouraged dimensional reasoning.

A derived electrical quantity could be represented by the way its numerical value changed when the underlying mechanical units changed.

Dimension was therefore not merely notation.

It exposed structural relations between systems of measurement.

Resistance with the dimensions of velocity

In the electromagnetic system, resistance has the dimensions of a velocity.

That does not mean resistance physically is motion.

It means the dimensional transformation of the electrical quantity follows the same combination of length and time.

Such results made visible connections that could otherwise remain buried in definitions.

The British Association resistance unit was chosen at ten million metres per second in the relevant dimensional representation.

The numerical conventions themselves became part of the developing electrical system.

Back to the velocity

The ratio between electrostatic and electromagnetic measures had already entered Maxwell's electromagnetic theory of light.

In Chapter 10 it supplied a characteristic velocity of:

310,740,000 metres per second

from Weber and Kohlrausch.

But Maxwell himself had warned in 1865 that this came from:

| “the only set of experiments we as yet possess.”

That qualification points directly toward the next measurement.

The 1868 comparison

Maxwell designed an experiment to compare electrostatic and electromagnetic force directly.

The paper appeared in the Philosophical Transactions in 1868.

Electrostatic attraction between charged disks was balanced against electromagnetic forces produced by currents in coils.

The theoretical ratio of units had become the object of a direct experiment.

A collective measurement

The experiment was not Maxwell alone with an apparatus.

John Peter Gassiot supplied what Maxwell called his:

| “magnificent battery of 2600 cells”.

Hockin:

| “undertook the whole work of the comparison of the currents by means of the galvanometer and shunts”.

The result therefore belongs to a network of apparatus, calibration and skilled observation.

The result: 288 million

The mean value reported was approximately:

288,000,000 metres per second.

That number matters because Chapter 10 left the electrical side open.

It is about seven percent below Weber and Kohlrausch's 310,740,000 m/s.

It is also about 3.4 percent below Foucault's 298,000,000 m/s.

The new measurement therefore does not make the old numerical agreement simply tighter.

The 1868 value lies below every optical value Maxwell had printed in 1865, Foucault's included.

A second electrical set

In 1865 Maxwell had spoken of the agreement based on the only electrical experiments then available.

In 1868 he helped produce another determination himself.

The result differed substantially.

This is precisely what it means for measurement to test a theoretical identification.

The theory did not collapse because one measured ratio shifted.

But neither could the identity be defended by citing the original near equality as if metrology had stopped in 1856.

The theory survives moving numbers

The electromagnetic theory of light had already acquired another support by this point.

In 1865 Maxwell had derived electromagnetic propagation from the field equations rather than only through the vortex-cell mechanism.

The comparison with light therefore belonged to a growing network of theoretical and experimental relations.

Individual numerical determinations could move while the larger structure remained under test.

The note on electromagnetic light

Maxwell's 1868 paper also includes a note explicitly concerned with the electromagnetic theory of light.

Its presence is important because it shows that the ratio measurement was not an isolated exercise in metrology.

The determination remained tied to the question raised in 1861–65: whether the characteristic electromagnetic velocity corresponded to optical propagation.

Technology is not merely application

Telegraphy created practical pressure for stable electrical standards.

Cable behaviour raised problems of resistance, retardation and signal transmission.

Physics did not simply generate theory first and hand it to technology later.

Engineering helped determine which quantities required precise measurement.

The direction of influence was reciprocal.

Cambridge

In 1871 Maxwell became the first Cavendish Professor of Experimental Physics at Cambridge.

The appointment represented an institutional development as well as a personal one.

Cambridge possessed a formidable mathematical tradition.

The new laboratory programme made precision experimental work part of university physics in a more systematic way.

The Cavendish Laboratory

The laboratory was built around apparatus, reproducibility and measurement.

Students had to learn not merely equations but how physical quantities became reliable numbers.

Experimental physics required instruments, procedures, standards and calibration cultures.

Theoretical concepts entered material practice.

Henry Cavendish

In July 1874 Maxwell gained access to Henry Cavendish's unpublished electrical manuscripts.

He spent years reconstructing and editing them.

The resulting *Electrical Researches of the Honourable Henry Cavendish* appeared in October 1879, only a month before Maxwell's death.

This was not antiquarian work detached from contemporary science.

Old experiments could still constrain living theories.

An inverse-square null test

Cavendish had used a null method to investigate the inverse-square law of electrical force.

Maxwell and Donald MacAlister repeated and refined the experiment.

If the force follows an exact inverse-square law, a particular interior electrical effect should vanish.

They looked for the departure.

They did not detect it.

The resulting bound on the exponent was about:

$$\pm 1/21,600$$

compared with Cavendish's approximate:

$\pm 1/50$.

The improvement was roughly four hundredfold.

Measurement as constrained absence

Nothing visibly happening can be a powerful result when the experiment specifies what should have happened under an alternative law.

This is the logic of a null test.

The absence is not empty.

It excludes possibilities.

The same structure has appeared elsewhere:

Saturn's persistence ruled out unstable constitutions.

A failed colour match revealed observer difference.

Specific heat ruled against parts of kinetic theory.

A null electrical effect constrained the force law.

The Treatise begins with measurement

Maxwell's 1873 Treatise on Electricity and Magnetism begins:

| "ON THE MEASUREMENT OF QUANTITIES."

That ordering should not be converted into a complete philosophy from one heading.

But it demonstrates the prominence Maxwell gave to measurement in presenting mature electromagnetism.

Before the theory can compare quantities, it must say what their numbers mean.

Measurement does theoretical work

Measurement therefore performs several roles.

It creates reproducible standards.

It reveals dimensional relations.

It allows independent physical processes to be compared.

It exposes disagreement between theoretical and experimental quantities.

It can constrain laws through null results.

And its own values can change.

A theory that relies on measurement has to survive that movement.

Toward rebuilding

By Maxwell's death, electromagnetism existed as far more than a set of equations.

It was embedded in standards laboratories, telegraphic engineering, precision apparatus, the Cavendish Laboratory, a major Treatise and an international research community.

The next generation did not merely accept this inheritance.

They rewrote it.

Chapter 16

Rebuilding Maxwell

The equations now called Maxwell's equations are not simply the equations Maxwell wrote.

That sentence sounds surprising because the later reconstruction was extraordinarily successful.

Maxwell's theory was mathematically rich, conceptually layered and notationally difficult.

Later physicists selected, compressed and reformulated it.

To understand what they inherited, we need to distinguish what Maxwell himself contributed from what his successors built.

Twenty equations

In the 1865 paper Maxwell organised:

twenty variable quantities

and

twenty equations

into eight groups.

The modern four-equation vector presentation was not already present in this form.

The compression came later.

Hamilton before Maxwell

The words scalar and vector were introduced by William Rowan Hamilton in the development of quaternions during the 1840s.

Maxwell inherited that mathematical vocabulary.

He did not invent it.

But he became an important participant in adapting vectorial language to physics.

Maxwell's vector-potential

Maxwell did not merely use some unnamed quantity that later generations called a vector potential.

He himself repeatedly used the term:

| “vector-potential.”

The Treatise speaks of the vector-potential of magnetic induction and of electric current.

This is part of Maxwell's own mathematical authorship.

Curl

Maxwell also contributed terminology that survives directly.

In a paper read on 9 March 1871, published in the Proceedings of the London Mathematical Society as Remarks on the Mathematical Classification of Physical Quantities, Maxwell proposed the term curl for a rotational vector operation.

The historical attribution belongs to Maxwell.

This produces a useful paradox.

Maxwell supplied pieces of the later vector vocabulary.

He still did not write modern vector calculus.

Gibbs

J. Willard Gibbs developed a more economical vector analysis partly in response to the quaternionic mathematical world through which he had encountered Maxwell.

His Elements of Vector Analysis, circulated privately from 1881 and again in 1884, helped detach dot and cross operations from the full quaternion framework.

The mathematical language changed.

Heaviside

Oliver Heaviside began reformulating electromagnetism in vector language from 1884 onward in *The Electrician*.

The transformation was dramatic.

Maxwell's extensive set of component relations could be represented through four compact vector equations.

This was not merely typographical abbreviation.

A new notation reorganised which structural features were immediately visible.

What compression removes

The modern equations no longer display the historical path through:

vortices,

idle wheels,

elastic dielectric cells,

mechanical stress constructions,

or Maxwell's successive representational changes.

A reader encountering only the final vector equations can easily imagine that the theory emerged in that form.

It did not.

What compression retains

The reformulated theory retains relations involving:

electric and magnetic fields;

electromagnetic induction;

changing electric displacement;

magnetic induction without sources, expressed as zero divergence;

and the structure required for electromagnetic propagation.

The form changes.

The relational core survives.

Hertz defines Maxwell by equations

Heinrich Hertz later gave a revealing description of the reconstruction.

In the 1893 English edition of *Electric Waves* he wrote:

“Maxwell’s theory is Maxwell’s system of equations.”

The statement comes from a physicist actively rebuilding the theory.

Its significance is enormous.

The theory is being identified less with Maxwell’s mechanical ether pictures and more with a mathematical system that successors themselves have reorganised.

Hertz’s experiments

Hertz then brought electromagnetic propagation into the laboratory in the late 1880s.

He generated and detected oscillatory electrical disturbances.

Reflection, interference and other wave phenomena provided powerful experimental evidence for electromagnetic propagation through space.

But the path to agreement was not perfectly clean.

Trouble along wires

Some of Hertz’s measurements suggested that propagation along wires varied with wavelength and differed from propagation through air.

Those results did not initially fit Maxwellian expectations neatly.

Later experiments by Édouard Sarasin and Lucien de la Rive obtained behaviour closer to what the theory required.

The final historical resolution was technically complex.

The important point here is enough:

“Hertz confirmed Maxwell” is true only at a high level.

The actual experimental programme contained disagreement, reinterpretation and further measurement.

From inferred wave to laboratory object

This was nevertheless an enormous epistemic transformation.

Maxwell had inferred electromagnetic propagation theoretically.

Hertz could generate disturbances, detect them elsewhere and manipulate their wave-like behaviour.

The electromagnetic wave became an experimental object rather than merely a permitted theoretical mode.

Radio comes later

The existence of electromagnetic waves would eventually support wireless communication.

But Maxwell was not predicting modern radio as a technology.

Hertz himself was pursuing physical questions, not implementing the communications systems that later engineers would build.

Scientific possibility and technological trajectory should remain distinct.

The Maxwellians

In Britain, figures such as Heaviside, George Francis FitzGerald and Oliver Lodge formed part of what historians have called the Maxwellian tradition.

They developed Maxwell's theory rather than merely repeating it.

Lorentz belongs to a related but distinct continental reconstruction.

The international afterlife should therefore not be flattened into one school.

Authorship and inheritance

The modern theory contains contributions from multiple stages.

Hamilton supplied scalar and vector terminology.

Maxwell introduced the vector-potential and proposed curl.

Gibbs developed vector analysis.

Heaviside radically compressed the equations.

Hertz defined and tested the equation-centred theory.

Lorentz would rebuild electromagnetic matter.

A name can mark ancestry without implying exclusive authorship of every later form.

The modern four equations

Calling the compact system “Maxwell’s equations” remains historically reasonable.

Maxwell established essential relations and the electromagnetic theoretical architecture from which they descend.

But the label should not conceal the reconstruction.

The four equations are a historical inheritance.

Not a photographic reproduction of Maxwell’s page.

Rebuilding as evidence of theoretical strength

A scientific theory capable of major representational change without losing its predictive structure possesses a particular kind of robustness.

Maxwell’s electrodynamics could move:

from mechanical imagery,

to general equations,

to vector reformulation,

to experimental wave physics.

The transformations were substantial.

The theory did not remain identical.

But neither did it dissolve.

What remains unresolved

The ether still survives in many late nineteenth-century versions.

Moving bodies still create difficult problems.

The relation between optical propagation, electrodynamics and motion remains unsettled.

And Maxwell himself had already recognised one form of that difficulty before his death.

The next chapters follow both what the theory retained and the problem of motion that it passed to its successors.

Chapter 17

What Was Kept, What Was Removed, What Returned

A theory does not survive by remaining unchanged.

Maxwell's electromagnetic theory is an unusually clear case.

Between the 1860s and the opening years of the twentieth century, the theory was repeatedly rewritten. Some of its mechanical components disappeared. Some mathematical relations survived. Some physical concepts changed their referents. Others acquired new experimental meanings.

The result was not the gradual uncovering of a finished theory already hidden inside Maxwell's papers.

It was reconstruction.

1865: the first removal happens inside Maxwell's own work

The first important removal occurred before Maxwell died.

In *On Physical Lines of Force*, the electromagnetic medium had been represented through molecular vortices, intermediate particles and elastic deformation.

By *A Dynamical Theory of the Electromagnetic Field*, received in 1864 and published in 1865, Maxwell no longer required that particular machinery.

He said explicitly that he now avoided the earlier hypothesis of a particular motion and strain. Mechanical expressions such as electric momentum and electric elasticity were to be regarded as:

| “illustrative, not as explanatory.”

The distinction matters.

The detailed vortex mechanism was withdrawn from that derivation.

The medium was not.

Maxwell still described the electromagnetic field as containing matter in motion and referred to an ethereal medium filling space.

So even within Maxwell's lifetime, different layers of the earlier representation already had different futures.

Removed: the idle wheels

The easiest component to follow is the most picturesque.

The intermediate particles or idle wheels of the 1861 mechanism do not survive into mature electromagnetic theory.

Their disappearance is particularly instructive because Maxwell had never assigned them strong evidential status.

He had already said that he would not willingly assent to the proposed connexion as an electrical hypothesis.

The later theory could therefore retain relations that the idle wheels had helped make mechanically conceivable without retaining the wheels themselves.

Removed: the molecular vortices

The specific vortex cells likewise disappeared from the main electromagnetic derivation.

Modern magnetism is not the rotation of Maxwellian ether cells.

But it would be too simple to write:

vortices false, equations true.

The vortices had done historical work.

They helped Maxwell construct stresses, connect magnetism with rotation, incorporate dielectric displacement and calculate a transverse wave velocity.

A later representation could perform those tasks without preserving the original mechanism.

That is a change of carrier, not evidence that the carrier had been useless.

1871: a word survives

Representational survival can occur at a much smaller scale.

In 1871 Maxwell proposed the term curl for the rotational vector operation that later became standard in vector analysis.

The mature mathematical notation was not yet present.

Gibbs and Heaviside would later transform the language substantially.

But the term itself crossed that transformation.

This is a modest example, precisely because it can be dated.

1873: the vector-potential is already Maxwell's term

The *Treatise on Electricity and Magnetism* gives another correction to retrospective language.

The vector potential was not merely a later name attached to something vaguely present in Maxwell.

Maxwell himself repeatedly wrote of the vector-potential, including the vector-potential of magnetic induction.

Later physicists changed its notation, mathematical setting and preferred interpretation.

They did not invent the term after Maxwell.

This distinction matters because the afterlife of a theory includes both preservation and re-description.

1884: energy acquires a directional flow

Maxwell had already assigned energy to the electromagnetic field.

In 1884 John Henry Poynting gave the transfer of electromagnetic energy an explicit local directional formulation.

The later quantity bearing his name describes the flow of electromagnetic energy through space.

This is not simply an equation Maxwell forgot to write.

It is a post-Maxwellian development built within the field framework his theory helped establish.

What survives is therefore not an unchanged concept of field energy.

It is a research programme capable of further articulation.

1884 onward: Heaviside changes the equations' visible structure

Beginning in 1884, Oliver Heaviside reformulated Maxwellian electrodynamics using vector methods.

The twenty equations in twenty variables of Maxwell's 1865 presentation were reorganised into a far more compact system.

This did more than save ink.

Notation changes what is easy to see.

Relations that had been distributed across components became visible as divergence and curl relations.

The electromagnetic theory increasingly looked unlike the papers from which it descended.

Yet enough structure remained that physicists continued to call it Maxwellian.

1888 and 1890: Hertz makes propagation experimental

Heinrich Hertz's experiments in 1888 and his subsequent publications around 1890 transformed the evidential status of electromagnetic propagation.

Maxwell had derived propagating electromagnetic disturbances.

Hertz generated and detected them in the laboratory.

Wave behaviour could be examined through reflection, interference and resonant electrical systems.

The theoretical mode became an experimentally manipulable phenomenon.

That did not mean every Hertz experiment matched Maxwellian expectations immediately. Measurements of propagation along wires produced difficulties and further experimental work.

Confirmation was itself historical.

But electromagnetic waves no longer belonged only to inference.

From 1892: Lorentz changes the architecture while retaining an ether

The disappearance of Maxwell's ether must be divided into stages.

In his electron theory from 1892 onward, Hendrik Lorentz retained an ether.

But it was no longer Maxwell's elastic mechanical medium of rotating cells, strains and internal mechanical motions.

The active theoretical architecture increasingly centred on electric charges and electromagnetic fields, while the ether functioned as a stationary background.

By the mid-1890s, the detailed mechanical properties Maxwell had attached to the medium were no longer doing the same explanatory work.

This is the first withdrawal:

the mechanical constitution of Maxwell's ether loses its explanatory role while an ether is still retained.

It must not be confused with what happens in 1905.

Matter: molecular polarisation survives transformed

Maxwell's dielectric picture has a different afterlife.

In 1862 he had imagined electricity displaced within molecules so that opposite electrical states appeared on opposite sides.

Later electron theories gave material polarisation a new microscopic basis through the displacement of bound charged constituents.

The mechanism is not Maxwell's.

But the broad physical idea that material dielectric polarisation corresponds to charge separation within matter survives in transformed form.

Changing polarisation also contributes an actual current of bound charge.

Here the nineteenth-century picture was not simply erased.

It was reconstructed around new microscopic entities.

Vacuum: displacement loses its mechanical carrier

Electric displacement in apparently empty space follows another path.

For Maxwell, space was not empty in the modern sense.

The electromagnetic medium filled it.

Displacement therefore belonged to a medium.

When the mechanical ether ceased to carry electromagnetic theory, the corresponding term in the field equations survived without requiring the displacement of a Maxwellian material substrate.

This may be the clearest example in the book of a mathematical relation outliving its first mechanical referent.

The same word crosses the transition.

The ontology does not.

1905: Einstein makes the ether unnecessary for his formulation

Einstein's 1905 paper marks a second, distinct stage.

He did not report that experiments had suddenly proved no ether existed.

His claim was theoretical: the introduction of a luminiferous ether would prove superfluous because the new formulation required neither an absolutely stationary space endowed with special properties nor a velocity assigned to empty space.

That distinction matters.

Lorentz could retain an ether while removing most of its Maxwellian mechanical work.

Einstein could formulate electrodynamics without needing the ether at all.

And acceptance of that conclusion by the physics community was not instantaneous.

The survival ledger must preserve those separate dates.

Kept: electromagnetic propagation

Propagation survives every major representational change considered here.

In 1862 it is a transverse mechanical vibration of an elastic electromagnetic medium.

In 1865 Maxwell derives electromagnetic disturbance through the field equations while retaining an ether.

In 1888 and 1890 Hertz makes such disturbances experimental.

In 1905 electrodynamics no longer requires a luminiferous mechanical carrier in Einstein's formulation.

The wave survives.

What a wave must be *in* changes.

Kept: field relations

The electric and magnetic field relations survive with extensive mathematical reconstruction.

Their notation changes.

Their grouping changes.

The variables preferred by different authors change.

Their interpretation changes.

Yet the network linking electric change, magnetic change, induction, charge and propagation becomes increasingly stable.

This is stronger historically than saying "Maxwell's equations survived".

It specifies what kind of continuity occurred.

Changed: what counts as Maxwell's equations

Maxwell's original equation systems were not four compact vector expressions.

Gibbs supplied part of the mathematical language.

Heaviside reorganised the electromagnetic equations from 1884 onward.

In the 1893 English edition of *Electric Waves*, Hertz's introduction states:

“Maxwell's theory is Maxwell's system of equations.”

The sentence is historically revealing precisely because the system he had in mind had already been rebuilt.

A theory can acquire a canonical form its principal originator never wrote.

Changed: the vector potential

The vector potential survived but changed status repeatedly.

Maxwell named it.

Later formulations sometimes treated potentials as convenient mathematical auxiliaries behind the electric and magnetic fields.

That hierarchy would not remain fixed.

As a deliberately marked look beyond this book's main 1905 horizon, Aharonov and Bohm in 1959 predicted quantum phenomena in which electromagnetic potentials cannot be dismissed merely as a redundant classical notation.

That is not Maxwell returning unchanged.

It is a later theory assigning new physical significance to a mathematical object with a Maxwellian history.

The ledger, dated

By 1865 the detailed vortex hypothesis had been removed from Maxwell's principal electromagnetic derivation.

In 1871 and 1873 Maxwell supplied terminology, including curl and vector-potential, that survived later mathematical reconstruction.

In 1884 Poynting gave electromagnetic energy transfer an explicit local directional formulation.

From 1884 onward Heaviside reorganised Maxwellian electrodynamics in vector form.

In 1888 and 1890 Hertz made electromagnetic propagation experimentally accessible and elaborated the electromagnetic-wave programme.

From 1892 through the mid-1890s Lorentz retained an ether while removing the need for Maxwell's detailed mechanical constitution of that ether.

In 1905 Einstein declared the introduction of a luminiferous ether superfluous to his formulation of electrodynamics.

In 1959, far beyond the chronological horizon of Maxwell's own theory, Aharonov and Bohm supplied a new quantum context in which electromagnetic potentials acquired renewed physical significance.

The sequence is not one removal.

It is a succession of representational changes.

What counts as the same theory?

This creates a genuine historical problem.

If mechanism, notation, ontology and even preferred variables change, what licenses the name *Maxwellian*?

Not textual identity.

Not preservation of every object Maxwell believed existed.

Continuity lies instead in an inherited network of problems, equations, experimentally testable relations and transformations.

The name marks genealogy.

It does not imply invariance.

What was kept

The most durable elements were not generally the most mechanically picturesque.

Electric and magnetic relations persisted.

Displacement persisted, differently in matter and vacuum.

Electromagnetic propagation persisted.

Energy associated with the field persisted and was extended.

The vector potential persisted through changing interpretations.

What was removed

Idle wheels disappeared.

Molecular vortices disappeared from the main electromagnetic derivation.

The elastic cellular constitution of the electromagnetic ether disappeared from later electrodynamics.

Eventually the ether itself became unnecessary to a major formulation of electrodynamics.

What returned

“Return” must be used cautiously.

The vector potential acquires renewed importance in twentieth-century quantum physics.

Microscopic polarisation returns in a form based on charged constituents rather than Maxwell’s molecular electricity.

These are genealogical continuities, not resurrection of Maxwell’s original objects.

The answer is not “Maxwell was right”

The survival ledger resists a binary judgement.

Idle wheels were not a natural electrical connexion; Maxwell had never claimed they were.

He was not right about molecular vortex cells as the constitution of the electromagnetic medium.

Later physics did not retain his mechanical ether.

Yet theoretical structures developed through those representations helped generate relations that survived increasingly severe reformulations and experiments.

Scientific success occurred at different layers.

A theory can die mechanically and survive structurally

This is the strongest conclusion Chapter 17 can support.

The detailed ontology of a theory may be removed while relations it helped expose remain productive.

But those relations do not pass untouched from one century to another.

They are rewritten, measured again, embedded in new theories and assigned new meanings.

Survival is therefore not permanence.

It is constrained transformation.

The final chapter now asks how that transformed Maxwellian inheritance entered the problem of moving bodies and relativity.

Chapter 18

From Maxwell to the Problem of Relativity

Maxwell died in 1879.

Einstein was born the same year.

The coincidence is memorable and almost useless.

There was no direct intellectual handoff from Maxwell to Einstein.

There was, however, a much more precise handoff from Maxwell's final work to one of the experimental problems that later entered the history of relativity.

It begins in Maxwell's last year.

March 1879: Maxwell asks how motion through the ether could be detected

On 19 March 1879 Maxwell wrote to David Peck Todd of the American Nautical Almanac Office.

The problem was the motion of the Solar System relative to the luminiferous ether.

If light propagated through an ether, motion relative to that medium might in principle be measurable.

But Maxwell identified an experimental difficulty.

In terrestrial measurements of the velocity of light, the beam normally travelled out and returned along the same path.

The effect of the Earth's motion on the round trip would therefore survive only at second order.

Maxwell said that the resulting change depended on the square of the ratio between the Earth's velocity and the velocity of light and was:

| “quite too small to be observed.”

That was not a declaration that ether drift was meaningless.

It was an estimate of experimental accessibility.

An astronomical route

Maxwell therefore considered an astronomical method.

He proposed observations involving the eclipses of Jupiter's satellites as a possible way to estimate the direction and magnitude of the Sun's motion relative to the luminiferous medium.

He described it as "the only method, so far as I know."

Maxwell died before the idea could become part of a sustained programme of his own.

The letter was published posthumously in 1880.

Then someone read it.

Michelson begins from Maxwell

Albert A. Michelson's 1881 paper *The Relative Motion of the Earth and the Luminiferous Ether* explicitly opens its experimental problem from Maxwell's letter.

Michelson writes that Maxwell had pointed out the astronomical method and the difficulty with terrestrial round-trip measurements.

Then Michelson disagrees with Maxwell's practical conclusion.

Using interference and the wavelength of light as a standard, he argues that the second-order effect, if it exists, should be measurable.

This is a genuine documentary chain:

Maxwell, 19 March 1879.

Posthumous publication, 1880.

Michelson cites Maxwell, 1881.

There is no need to invent a broader lineage when this narrower one is directly visible.

Michelson takes the terrestrial route anyway

The irony is instructive.

Maxwell had concluded that the terrestrial effect was too small for available methods.

Michelson's contribution was to devise a method intended to make precisely such a small difference observable.

Interferometry changed what counted as experimentally accessible.

This is another example of measurement altering the boundary between theoretical possibility and empirical test.

1881 was not the final experiment

Michelson's first experiment did not end the ether question.

The apparatus and calculation would be reconsidered.

In 1887 Michelson and Edward Morley performed the more famous interferometric experiment.

Its result did not reveal the expected ether drift.

But the standard story in which one null result destroys the ether and directly produces special relativity compresses decades of theoretical work into a false chain.

The null result became one constraint among several.

Lorentz changes the ether before Einstein removes the need for it

Hendrik Lorentz developed electron theory during the 1890s.

The ether remained.

But it was no longer Maxwell's elastic mechanical medium of cells, strains and vortices.

Matter was represented through charged constituents.

The electromagnetic field obeyed its equations in an immobile ether.

The mechanical architecture of Maxwell's ether had largely disappeared while the word ether remained.

This distinction was already important in Chapter 17.

It becomes essential here.

The ether did not pass directly from Maxwell's vortices to Einstein's rejection.

It changed before it became unnecessary.

Polarisation changes with it

Lorentz also supplied a new microscopic language for matter.

Dielectric polarisation could be represented through displacement of electrical charges within atoms or molecules.

This gave one part of Maxwell's dielectric picture a transformed afterlife.

The material medium contained charges that could actually move relative to one another.

At the same time, the universal elastic substrate Maxwell had used to carry displacement through apparently empty space was losing its mechanical role.

The transformations develop before Einstein

The mathematical prehistory of relativity was equally populated.

Voigt obtained a transformation connected with the wave equation in 1887.

Lorentz developed versions of local time and coordinate transformations in work of 1892, 1895, 1899 and 1904.

Larmor developed related transformations in 1897 and 1900.

Poincaré analysed clock synchronisation in 1900 and strengthened the relativity principle in 1904.

On 5 June 1905, before Einstein's paper was received later that month, Poincaré explicitly named the Lorentz transformations and stated that they formed a group.

None of those results is simply Einstein's special relativity in advance.

Together they prevent a solitary-genius reconstruction.

Einstein's Maxwell was already rebuilt

Einstein's 1905 paper begins not from Maxwell's 1861 vortices or even directly from the 1865 notation.

He begins with:

| “as usually understood at the present time”.

That qualification is historically important.

The theory he inherited had already passed through Hertz, Heaviside, Lorentz and others.

In the same 1905 paper Einstein refers to the Maxwell-Hertz equations.

The Maxwell confronting Einstein was therefore an inherited and reconstructed Maxwell.

The magnet and the conductor

Einstein opens with a familiar electromagnetic asymmetry.

A magnet moving relative to a conductor and a conductor moving relative to a magnet can produce the same observable current.

Yet the conventional theoretical description assigns different mechanisms depending on which object is said to move.

Einstein treats this asymmetry as a sign that the distinction should not belong to the phenomena themselves.

The problem arises inside mature electrodynamics.

It is not evidence that Maxwell had anticipated relativity.

A new kinematics of space and time

Einstein's solution reorganises the concepts of space, time and simultaneity around two principles:

the relativity principle,

and the constancy of the velocity of light.

In 1905 this is properly described as a new kinematics of space and time.

The later geometric spacetime formulation belongs especially to Minkowski's work after 1905.

That distinction prevents another small but persistent hindsight error.

Ether becomes superfluous

Einstein's statement is also more precise than the slogan "the ether was disproved."

He writes that:

"The introduction of a 'luminiferous ether' will prove to be superfluous."

The claim is about theoretical necessity.

His formulation does not require an absolutely stationary space carrying special mechanical properties.

It does not amount to a report that an experiment had directly observed the absence of ether.

Maxwell did not predict this

Maxwell retained an ether.

He treated it as physically meaningful.

Even in 1879, his letter to Todd asks about motion relative to the luminiferous medium.

It would therefore reverse the historical evidence to portray him as already holding Einstein's position.

What Maxwell supplied was not the later solution.

He helped create the electromagnetic structure within which the moving-body problem became acute.

But Maxwell did see the experimental problem

The opposite claim would also be wrong.

The Todd letter shows that Maxwell himself considered whether motion relative to the ether could be detected.

He understood that terrestrial round-trip methods produced only a second-order effect.

He proposed an alternative.

Michelson explicitly took up the problem.

This is a stronger historical statement than saying vaguely that “Maxwell paved the way for Michelson”.

The documentary link exists.

The null result does not act alone

Michelson’s experiments matter because they interacted with theory.

Lorentz contraction hypotheses.

Electron theory.

The relativity principle.

The transformation properties of Maxwellian electrodynamics.

The problem of synchronising clocks.

The status of the ether.

No one experimental datum automatically selected Einstein’s conceptual reconstruction.

Historical causation is not mathematical entailment.

Einstein’s retrospective Maxwell

There is another Maxwell we must now distinguish from the historical one.

In 1931, for the centenary of Maxwell's birth, Einstein described the work of Faraday and Maxwell as a major transformation in the conception of physical reality. In the English translation later collected in *Ideas and Opinions*, his retrospective contrast moves from the Newtonian picture of material points and forces toward "continuous fields, not mechanically explicable".

It is not contemporaneous evidence about what Maxwell thought he was doing.

It is evidence about Einstein's Maxwell.

What Einstein's retrospective narrative compresses

Einstein's centenary account is treated here as retrospective reception rather than as evidence for Maxwell's own nineteenth-century commitments.

Seen from 1931, that contrast is intelligible.

Seen from 1865, it compresses important intermediate commitments.

Maxwell's own electromagnetic field was still associated with:

matter in motion,

an ethereal medium,

elasticity,

energy,

and continuing attempts at mechanical intelligibility.

At the same time, he explicitly withdrew particular mechanisms and said certain mechanical terms were "illustrative, not as explanatory".

The historical transition was therefore not:

Newtonian particles, Maxwell's nonmechanical field.

It proceeded through intermediate combinations.

Retrospective truth and historical sequence

Einstein's retrospective contrast captures something real about the long-run transformation of physics.

Fields did become central objects not reducible to Maxwell's mechanical ether models.

But that retrospective formulation belongs to 1931.

It describes the history from the far side of Lorentz, Hertz, relativity and quantum theory.

Used as an account of Maxwell's own conceptual position, it would import the destination into the journey.

That is precisely the hindsight error this book has tried to avoid.

Maxwell's actual inheritance

What reaches Einstein from Maxwell is therefore not one intact theory.

It is a reconstructed network:

electromagnetic field relations,

a characteristic velocity,

electromagnetic light,

moving-body problems,

experimental ether questions,

and mathematical equations already reformulated by successors.

The inheritance is relational and problematic.

Not mechanical.

The wrong endings

We can now rule out three easy conclusions.

Maxwell foresaw Einstein.

No.

Maxwell made relativity inevitable.

No.

Einstein merely completed Maxwell.

No.

Each removes the historical work performed between them.

A more exact ending

Maxwell constructed an electromagnetic theory whose successful relations survived substantial changes in mechanism and representation.

Those relations generated new problems when combined with moving bodies and the speed of light.

Maxwell himself encountered one experimental form of the ether-motion problem in 1879.

Michelson took it up directly.

Lorentz, Larmor and Poincaré altered its mathematical and physical framework.

Einstein reorganised the kinematics in 1905.

This is influence without prophecy.

Continuity without identity.

Inheritance through reconstruction.

That is a more demanding historical connection than the simple claim that one genius anticipated another.

Epilogue

Thinking the Invisible

We began with a disadvantage.

We know too much.

We know that electromagnetic waves exist.

We know that Maxwell's molecular vortices did not survive as the mechanism of electromagnetism.

We know that the mechanical ether eventually ceased to be required by electrodynamics.

We know that kinetic theory developed beyond Maxwell.

We know that relativity changed the kinematics of space and time.

We know that quantum theory changed the terms of problems Maxwell left unresolved.

Maxwell knew none of those futures.

The purpose of this book has therefore not been to ask how close he came to us.

It has been to ask what could legitimately be inferred when the mechanism itself remained hidden, disputed or provisional.

Several kinds of invisible

The invisible changed from problem to problem.

Inside strained glass, the hidden object was a mechanical state inferred through optical consequences.

In colour, physiological response was inferred through reproducible matches.

At Saturn, unseen constitution was constrained by observation and dynamical stability.

In gases, enormous populations of molecules were represented statistically because individual trajectories could not be followed.

In electromagnetism, states and possible mechanisms were distributed through regions of space that could not be inspected directly.

These problems did not demand one method.

That is already important.

Several ways of inferring

Maxwell's work employed several evidential structures.

Observe the consequences of hidden strain.

Construct quantitative perceptual equivalences.

Eliminate dynamically impossible constitutions.

Replace untraceable individual trajectories with statistical distributions.

Construct a hypothetical mechanism and calculate its consequences.

Change the mechanism and see which relations remain usable.

Compare quantities defined through independent measurement systems.

Use a null result to constrain a possible law.

Any unity in Maxwell's work must therefore survive substantial methodological diversity.

It cannot consist simply in his doing the same thing repeatedly.

What Maxwell actually qualified

Across that diversity, Maxwell repeatedly marked the status of representations.

In 1855 his imaginary fluid was not even a hypothetical fluid introduced to explain actual phenomena.

In 1860 his elastic-particle gas would become a physical analogy only if its properties corresponded to gases.

In 1861 he would not willingly assent to the proposed idle-wheel connexion as an electrical hypothesis.

In October 1861 the velocity comparison could give strong reason to believe in a common medium “whether my theory is a fact or not”.

In 1862 the dielectric relations were independent of a theory about the internal mechanism of dielectrics.

In that same construction he admitted that one required tangential action had not been explained.

And in 1864–65 he wrote that, in the present paper, he avoided the earlier hypothesis of a particular motion and strain, while mechanical expressions were to be treated as “illustrative, not as explanatory”.

The last wording matters.

He did not announce that the older mechanism had been permanently abandoned.

He avoided it in that paper.

The candidate proposition

At the beginning of its test, this book fixed a candidate proposition.

Maxwell appeared repeatedly to use richly specified mechanisms as productive working representations while withholding complete commitment to their literal truth, and to preserve useful relations when a mechanism was changed or set aside.

The book also stated conditions under which that proposition would weaken or fail.

They were the conditions stated in the Prologue: the candidate pattern would be weakened or defeated if Maxwell’s methods differ fundamentally from one domain to another, if the same practices are equally characteristic of his contemporaries, if his relation to experiment changes radically between subjects, or if the supposed unity appears only after later historians reorganise his work.

These conditions were not invented at the end to fit the evidence.

They were stated before the chapters were assessed.

Now they can be scored.

First condition: did Maxwell's methods differ fundamentally between domains?

There is no single Maxwellian procedure running unchanged from geometry to electromagnetism.

Colour matching is not Saturnian stability analysis.

Saturnian elimination is not kinetic statistics.

Kinetic statistics is not electrical metrology.

Electrical metrology is not mechanical analogy.

So if the proposition required one invariant procedure, it would fail.

But that was not the candidate.

The narrower recurring feature concerns how representations and evidential commitment were handled.

On that level there is genuine recurrence.

Maxwell repeatedly distinguishes what a representation can calculate or organise from what has yet earned physical commitment.

The recurrence appears in different technical forms rather than in one universal algorithm.

Score: the condition partly bites, but does not by itself destroy the narrower proposition.

Second condition: were the same practices characteristic of contemporaries?

Here the challenge is much stronger.

Rankine and Thomson prevent any claim that Maxwell invented provisional mechanical modelling or the separation of mathematical usefulness from literal physical commitment.

Thomson

In June 1847 William Thomson sent Faraday a mechanical representation involving strain propagated through an elastic solid.

He explicitly called what he had written:

“merely a sketch of the mathematical analogy”.

He also said that he had not ventured to make it the foundation of a physical theory.

Yet he wrote that such a theory “would also, when taken in connection with the undulatory theory of light, in all probability explain the effect of magnetism on polarized light”.

This is before Maxwell’s electromagnetic programme.

The separation between a productive representation and commitment to its literal physical truth therefore cannot be identified as a uniquely Maxwellian move.

Rankine

Rankine makes the test harder still.

His *Outlines of the Science of Energetics* was read on 2 May 1855.

There he argued that a hypothetical theory may be necessary as a preliminary step toward an abstractive theory, while insisting that general relations should be freed from the uncertainty that remains attached even to strongly confirmed mechanical hypotheses.

During the same year he was also actively developing his molecular-vortex programme.

His paper *On the Hypothesis of Molecular Vortices, or Centrifugal Theory of Elasticity, and its Connexion with the Theory of Heat* appeared in November 1855.

There is therefore no justified sequence in which Rankine first used vortices and later left them behind for energetics.

The programmes were concurrent.

That strengthens the comparison.

A rich mechanical hypothesis and a deliberate attempt to make general relations independent of its uncertainty existed together.

Rankine is similar, but not identical

The second half of the candidate nevertheless requires precision.

Maxwell in 1865 explicitly says that in that paper he avoids the earlier particular mechanical hypothesis while retaining electromagnetic relations developed through the programme.

Rankine's 1855 methodological position is somewhat different.

He sought to make the general laws independent of the uncertainty of mechanical hypotheses while continuing to develop the vortex hypothesis itself.

So Rankine demonstrates:

rich mechanism,

qualified commitment,

and relations whose certainty need not depend on that mechanism.

What the evidence does not establish is that he discarded the mechanism and then preserved the relations after its abandonment.

The difference is real but narrow.

And Maxwell himself later continued to discuss vortex explanations, so even his history should not be converted into a clean one-way progression.

The comparative outcome

The strong distinctiveness proposition fails.

The evidence supports the outcome allowed from the beginning: Maxwell is not meaningfully distinctive in kind once the correct comparison class is introduced.

That is the result.

Rankine and Thomson show that the underlying methodological resources belonged to a broader nineteenth-century scientific culture.

What remains demonstrable without making another unsupported comparison is this:

within Maxwell's own work, the pattern recurs across many different scientific domains.

That is a statement about Maxwell's corpus.

It does not rank him against Thomson, Rankine or every other nineteenth-century physicist by breadth.

Third condition: did Maxwell's relation to experiment change radically between subjects?

The answer is: substantially, yes.

But not arbitrarily.

The form of empirical constraint changes with the problem.

In the optical study of elastic solids, controlled observation tests how hidden stress appears through polarised light.

In colour, quantitative matching is itself the experimental operation.

Saturn cannot be manipulated experimentally; observation constrains candidate constitutions while dynamics eliminates unstable possibilities.

In kinetic theory, laboratory measurements of viscosity directly confront molecular models, and one of those measurements helps drive Maxwell toward an interaction law that later evidence weakens.

In electromagnetism, the ratio of electrical units supplies a quantitative test of a propagation velocity.

In 1868 Maxwell and Hockin measure that relation directly and obtain a substantially different number.

With MacAlister, a null experiment constrains deviations from the inverse-square law.

Governors are treated largely through mathematical stability analysis of engineered mechanisms.

These relations to experiment are not the same.

But there is a weaker continuity.

In each case Maxwell asks what observable constraints a representation must survive.

The type of observation changes because the accessible evidence changes.

Score: this condition bites materially. It rules out a strong unity of experimental procedure, while remaining compatible with a weaker unity at the level of evidential constraint.

Fourth condition: is the unity mainly a later historian's construction?

This is the most difficult condition.

The links among glass, colour, Saturn, molecules, governors and electromagnetism are assembled here by the author.

Maxwell never wrote a document saying that all these episodes instantiated one philosophy of representation.

Chapters 13 and 14 have already refused to infer such a hidden programme.

That refusal must remain.

There is therefore a genuine risk that any cross-domain unity is produced retrospectively.

But the case is not wholly retrospective.

The individual qualifications on which the comparison rests are Maxwell's.

He explicitly grades the status of the imaginary fluid.

He conditions the molecular analogy.

He withholds assent from the idle-wheel connexion.

He separates dielectric relations from internal dielectric mechanism.

He distinguishes the status of his 1865 illustrative mechanical language.

The historian is responsible for placing these episodes beside one another.

The qualifications themselves are not the historian's invention.

Score: this condition partly bites. A unified Maxwellian philosophy is not demonstrated. A recurrent documentary pattern is.

What the four conditions leave standing

The test therefore does not produce a coronation.

It removes several stronger claims.

There was no single method identical across Maxwell's sciences.

His relation to experiment differed greatly among problems.

Comparable forms of provisional modelling existed in Thomson and Rankine.

And the cross-domain synthesis belongs partly to retrospective historical analysis.

What remains is narrower:

Maxwell's surviving documents repeatedly show him separating, to different degrees, the utility of a representation from the evidential status of its underlying mechanism.

That statement survives the test.

A further finding: relations can outlive mechanisms

The survival of relations is important, but it is not one of the four original failure conditions.

It is a separate result.

In electromagnetism, displacement and the propagation relation continue when Maxwell avoids the earlier specific vortex machinery.

In kinetic theory, the velocity distribution survives substantial changes in the assumed intermolecular interaction.

In electrical measurement, the theoretical identity under test survives even while successive measured values move.

These survivals do not prove the mechanisms false or irrelevant at the moment of discovery.

They show that different layers of a theory can have different historical lifetimes.

Theories do not fail as indivisible wholes

Kinetic theory makes this particularly visible.

The distribution survives.

Hard spheres do not.

Density-independence of viscosity gains support.

The measured temperature law pushes Maxwell toward an inverse-fifth-power interaction, but the empirical proportionality itself is later weakened.

Specific heats remain a major unresolved difficulty.

There is no single date on which “Maxwell’s kinetic theory” changes from wrong to right.

Its components acquire different evidential histories.

Electromagnetism behaves similarly

The idle-wheel connexion disappears.

The detailed vortex machinery ceases to be required in the 1865 derivation.

Electric displacement remains.

The connection between electromagnetic propagation and light remains.

The velocity evidence itself changes.

The almost perfect-looking comparison reported privately in 1861 is not the same comparison printed in 1862.

Foucault’s later measurement widens the discrepancy.

Maxwell’s own 1868 electrical determination places the electrical value below every optical estimate then available.

Yet the electromagnetic theory of light becomes stronger.

The conclusion survives its first numbers because the network of reasons supporting it expands.

Measurement participates in theory

Measurement is therefore not merely judgement delivered after theory.

The electrical systems of units help create the quantity that becomes comparable with light.

Telegraphy creates pressure for reproducible resistance standards.

The 1868 comparison changes the numerical evidence.

Null experiments constrain possible laws by demonstrating what fails to appear.

Measurement helps determine which relations can be stated and tested.

Stability supplies another kind of structure

Saturn, governors and statistical physics produce a different recurrence.

The central question becomes what happens under disturbance.

Can the configuration persist?

Does correction decay or amplify deviation?

Can macroscopic regularity survive microscopic variability?

Again, the commonality is analytical, not evidence of a single private programme.

Maxwell's documents show the cases.

The historian places them together.

Kirchhoff marks another possible stance

Kirchhoff provides a useful limiting comparison.

In the preface to his 1876 lectures on mechanics he defined its task as describing the motions occurring in nature completely and in the simplest possible way.

He then clarified that the task was to state which phenomena occur, not to determine their causes.

That is more restrictive than Maxwell's usual practice.

Maxwell repeatedly sought physical mechanisms even when he withheld full commitment to them.

Kirchhoff's formulation shows that nineteenth-century mathematical physics contained other legitimate answers to the question of how much mechanism science required.

The later Maxwell must remain later

The same discipline applies to Einstein.

Einstein's 1931 centenary essay is titled, in *Ideas and Opinions*, "Maxwell's Influence on the Evolution of the Idea of Physical Reality".

It belongs to the history of Maxwell's reception.

It does not tell us directly how Maxwell in 1865 understood the status of fields and ether.

By 1931, Hertz, Heaviside, Lorentz, relativity and quantum physics stood between Einstein and Maxwell.

The retrospective Maxwell is historically important.

But it is retrospective.

The observer also belongs inside the problem

Colour adds one final complication.

Observation is not always transparent.

Human observers participate in colour matching.

Individual differences matter.

Objectivity comes not from pretending the observer is absent but from constructing procedures through which the observer's contribution becomes controlled and reproducible.

The hidden structure can sometimes lie partly on the observing side of the experiment.

Invisible does not mean unconstrained

This is the broadest conclusion the evidence supports.

A hidden mechanism becomes scientifically productive only through constraints.

A vortex without consequences is imagery.

A molecular population without predictions is a story.

A field without measurable relations is a name.

A mathematical analogy without disciplined correspondence is decoration.

Maxwell's successful representations mattered because they could be made to encounter equations, measurements and failures.

Neither prophet nor formalist

Maxwell should not be made a prophet.

Prophecy erases evidential work.

Nor should he be turned into a modern formalist indifferent to physical mechanism.

He repeatedly sought physical intelligibility.

The historically interesting position lies between those caricatures.

He could work intensively with a mechanism without assigning every part of it the same evidential status.

He could preserve a useful relation when its representation changed.

And he could publish difficulties his own theory had not solved.

The answer to the question

The book began by asking:

How did Maxwell decide what physics could legitimately infer when the underlying mechanism remained hidden, disputed or perhaps not there to be found at all?

There is no single rule in Maxwell's writings that answers that question across every subject.

The evidence supports something more concrete.

He constructed representations.

He calculated their consequences.

He compared those consequences with what could be observed or measured.

He sometimes distinguished explicitly between the success of a relation and the truth of a mechanism.

He revised mechanisms when constraints changed.

And different parts of a theory survived for different lengths of time.

These practices were not Maxwell's alone.

That is one result of the comparison, not a qualification to hide.

Thinking the invisible

Maxwell's importance does not require a private scientific method unavailable to his contemporaries.

The evidence rejects that stronger claim.

What the documents show instead is a remarkable sequence of cases in which hidden structures were made scientifically tractable without their underlying mechanisms being equally secure.

The invisible was represented.

Calculated.

Compared.

Measured.

Disturbed.

Sometimes rejected.

Sometimes retained.

Sometimes transformed.

And sometimes a relation proved more durable than the mechanism first used to make it conceivable.

That is the historically defensible meaning of thinking the invisible.
