UNIVERSITY OF
CAMBRIDGE

Michaelmas Essays
2025 - 2026

Assignment 2

Structure in Motion:
Reanimating Poincaré's Epistemology for the 21st Century

R.T. van Vroonhoven

Wordcount: 2,200

Assignment 2

ESSAY TITLE
Structure in Motion:
Reanimating Poincaré's Epistemology for the 21st Century

CHOSEN QUESTION
Choose an argument developed by Poincaré and show its relevance for contemporary discourse on science.

This essay reanimates Henri Poincaré's structural epistemology for the challenges of 21st-century science. Poincaré argued that scientific knowledge is organised not as a mirror of reality but as a hierarchy of mathematical, theoretical, and empirical relations—a structure that permits rational progress without metaphysical realism. Milena Ivanova's influential three-tiered model refines this vision, demonstrating how such relational structure ensures continuity across revolutionary theory change.

Yet this very success prompts a deeper question: if epistemic structure enables scientific transformation, what are the dynamics of structural transformation itself? This essay argues that Poincaré's model must be understood not as a fixed architecture, but as a process of becoming. To this end, I reinterpret his hierarchy through Gilbert Simondon's philosophy of individuation, recasting its tiers as metastable crystallizations from a field of conceptual tensions. Finally, I ground this speculative move by showing its operational reality in contemporary probabilistic reasoning, specifically in Thomas Krak's formalisms of credal networks. Thus, the essay demonstrates that Poincaré's enduring relevance lies in prefiguring an epistemology suited for a world of complexity, uncertainty, and adaptive inference—an epistemology where knowledge itself is structure in motion.

Structure in Motion:
Reanimating Poincaré's Epistemology for the 21st Century

- R.T. van Vroonhoven

Abstract

How can we organise and update our knowledge in a world that is complex and constantly changing?

This essay examines Henri Poincaré's structural epistemology—the way we gain knowledge of the world by tracking its stable relational structures rather than its supposed intrinsic properties—in light of contemporary scientific challenges around complexity, uncertainty and changing models. It reconstructs Poincaré's layered account of scientific knowledge, in which 1) empirical laws are formulated within 2) conventions of geometry and mechanics, 3) themselves grounded in the basic structures of arithmetic (Poincaré 1905).

Building on Milena Ivanova's three-tier model, the essay shows how this architecture secures rational continuity across radical theory change without appeal to a fixed metaphysical picture of reality, while leaving open the question of how these very structures arise and change over time (Ivanova 2015).

To address this gap, the essay draws on Gilbert Simondon's philosophy of individuation, reinterpreting epistemic structures as metastable patterns that reorganise under pressure rather than simply being replaced (Simondon 2009). It then links this perspective to credal networks in imprecise probability theory, where the dynamics of 'interference' formally model the processes by which AI systems observe, reason about and predict the world under conditions of deep uncertainty (Walley 1991). On this view, Poincaré appears as a foundational thinker of epistemic structure in motion.

Introduction

Before the discovery of bacteria, many physicians explained disease through miasma theory: foul-smelling air, not invisible organisms, was thought to make people sick. When microbiology developed, that framework had to be revised so that germs, rather than vapours, did the explanatory work. A similar shift occurred in fin-de-siècle geometry, when non-Euclidean frameworks challenged the assumption that Euclidean space was uniquely true. If scientific frameworks can change this deeply, how can we organise and update our knowledge in a world that is constantly changing?

This essay takes Henri Poincaré's account of scientific structure as a starting point. He treats science not as a heap of facts, but as a layered system in which empirical laws, theoretical frameworks and basic mathematical structures work together to make inquiry possible (Poincaré 1905). Building on Milena Ivanova's reconstruction of this view, the first part of the essay lays out how this layered architecture is supposed to secure continuity across radical theory change while avoiding heavy metaphysical commitments (Ivanova 2015).

The second part asks how these very structures themselves arise and transform over time. To address that question, the essay brings Poincaré into conversation with Gilbert Simondon's ontology of individuation and with recent work on imprecise probabilities and credal networks, using these resources to sketch a picture of epistemic structure as something dynamic—structured enough to guide inquiry, but continually reshaped under pressure.

Poincaré on Structure, Convention, and Continuity

As Henri Poincaré observed, science is not built by simply piling up facts, but by arranging them into organised patterns that allow us to predict and explain what happens (Poincaré 1905). On their own, facts do not amount to knowledge; they become scientifically meaningful only when our observations are brought together into patterns that show how things hang together. From this perspective, science does not try to uncover things "as they are in themselves," but to describe relations that stay stable enough across different situations to guide action and inquiry. Poincaré understood scientific knowledge as layered, not in terms of what is most certain, but in terms of what each layer does.

Firstly, at the base, are simple mathematical habits, like being able to count indefinitely and using induction: if something holds for 1, and if holds for n whenever it holds for n-1, then we treat it as holding for all numbers. These are not read off from experience, but basic tools that let us measure, compare, and keep track of things like time in the first place. In that sense, they play the role of a specifically Poincaréan synthetic a priori.

Secondly, above this, sit the working assumptions of geometry and mechanics, for example treating space as Euclidean or taking Newton's laws as a starting point. These are not straightforward discoveries about the world, nor are they fixed by logic alone. Poincaré describes them as "disguised definitions": practical choices that are kept because they are simple, hang together well, and help bring many different facts under the same umbrella, but which can be revised if they stop working or more generative theories emerge.

Thirdly, at the most visible level, are the empirical laws: general statements drawn from observation that can be directly tested and changed when new evidence appears. These laws rely on the deeper layers for their exact formulation, but they can often be adjusted without immediately changing the underlying geometrical or mechanical framework.

This tiered view helps Poincaré explain how science can change deeply while still keeping a sense of continuity. A well-known example is Fresnel's equations for light diffraction and refraction. These equations were first developed in an ether theory of light, but they were later carried over unchanged into Maxwell's electromagnetic theory. What changed was the story about what light "really is," not the mathematical relations that successfully linked experiments together. For Poincaré, this shows that the real backbone of scientific objectivity lies in the stability of these relational patterns, even when the surrounding concepts and images are revised.

In summary, Poincaré's layered view explains how certain mathematical relations can survive radical theoretical change, but it leaves open how the layers themselves emerge and transform. Poincaré tells us why some structures are kept once they are in place, not how they first congeal or eventually give way. To address that deeper question of genesis and transformation, this essay explores Ivanova's model, and speculatively introduces Simondon's concept of individuation.

Ivanova's Three-Tier Model: Knowledge in Layers

Milena Ivanova turns Poincaré's implicit hierarchy into three explicit layers, each with its own role and kind of justification. 1) At the base are arithmetic and pure magnitudes: synthetic a priori judgements, grounded in basic intuitions of repetition and iteration, which give us the structures needed for counting, quantifying, and measuring. These are not optional conventions, but preconditions for doing empirical science at all (Ivanova 2015).

2) The middle tier contains the conventions of geometry and mechanics. Choices between Euclidean and non-Euclidean axioms, or between principles like inertia and relativity, act as “disguised definitions”: they are neither fixed by experience nor derivable from arithmetic, but are chosen for their simplicity, naturalness, and power to bring many phenomena under a single, coherent theory. Their justification is holistic and historical, depending on the long-term fruitfulness of the frameworks they support rather than on one decisive experiment.

3) At the top sit empirical laws: contingent generalisations directly connected to observation, testable and revisable as new data appear. These laws rely on the lower tiers for their formulation and interpretation, but can be adjusted or rejected without immediately overturning the underlying conventions or the most basic arithmetic structures (Ivanova 2015). Ivanova’s model mainly describes how epistemic structures support rational theory change. It clarifies how continuity is preserved when one theory replaces another, but says less about how those very structures first emerge, stabilise over time, and eventually transform.

Addressing this gap calls for a more dynamic account of how structures are formed, reshaped, and sometimes abandoned—an account that can make sense not only of continuity, but of becoming. The next section turns to Gilbert Simondon’s ontology of individuation to develop such a process-based view of structure.

From Static Layers to Dynamic Fields: The Question of Transformation

Gilbert Simondon’s ontology of individuation offers a way to think about how epistemic structures come into being, hold together for a time, and eventually change. Instead of treating reality as a collection of fixed entities, Simondon understands it as an ongoing process of becoming in which structured forms—physical, biological, or conceptual—emerge through the resolution of tensions within metastable fields (Simondon 2009). Metastable systems sustain a workable equilibrium while retaining unresolved incompatibilities, which makes them stable enough to function yet primed for transformation.

For present purposes, the key attraction of Simondon is that he treats structures as outcomes of ongoing processes rather than as starting points. Read in this way, Poincaré’s “layers” can be seen not as fixed levels of reality or knowledge, but as relatively stable resolutions within a field of tensions generated by mathematical practices, empirical findings and explanatory aims: they make inquiry possible by partially resolving these tensions, but remain open to revision when pressures shift.

Ivanova's Poincaréan Epistemic Hierarchy

EMPIRICAL LAWS

Contingent generalisations derived from observation (e.g. Boyle's law, Kepler's laws)

Directly testable and revisable in light of new evidence. They are the "output" of the scientific process.

Empirical adequacys

CONVENTIONS

The defining principles of geometry and mechanics (e.g., Euclidean vs. non-Euclidean axioms, Newton's laws of motion).

These are "disguised definitions" (Poincaré's term). They are not empirical facts nor logical truths, but pragmatic, freely chosen frameworks that organize experience and allow for the formulation of empirical laws. They are justified by their simplicity, convenience, and unifying power.

Conventional/pragmatic (based on long-term empirical success

SYNTHETIC A PRIORI

The preconditions for measurement, quantification, and coordination. They provide the basic structure of number, magnitude, and recurrence.

For Poincaré, these are synthetic a priori judgments. They are not derived from experience (a priori) but are nevertheless informative and foundational for constructing scientific knowledge (synthetic). They are not conventions—we do not choose them; they are the necessary conditions for any empirical inquiry.

They are grounded in the intuition of indefinite repetition (iteration).

When anomalies accumulate, epistemic structures undergo transductive reorganisation rather than simple collapse. Poincaré's hierarchy can then be read as a sequence of layered individuations: arithmetic's synthetic a priori structures resolve basic tensions around repetition, quantity, and recurrence; conventions in geometry and mechanics stabilise higher-order conceptual conflicts by providing coherent frameworks for representation and law-formulation; empirical laws are more fragile resolutions, highly sensitive to evidential shocks (Poincaré 1905; Friedman 2001). On this view, scientific revolutions appear as field-wide transductions that preserve certain relational invariants while reconfiguring the surrounding epistemic field.

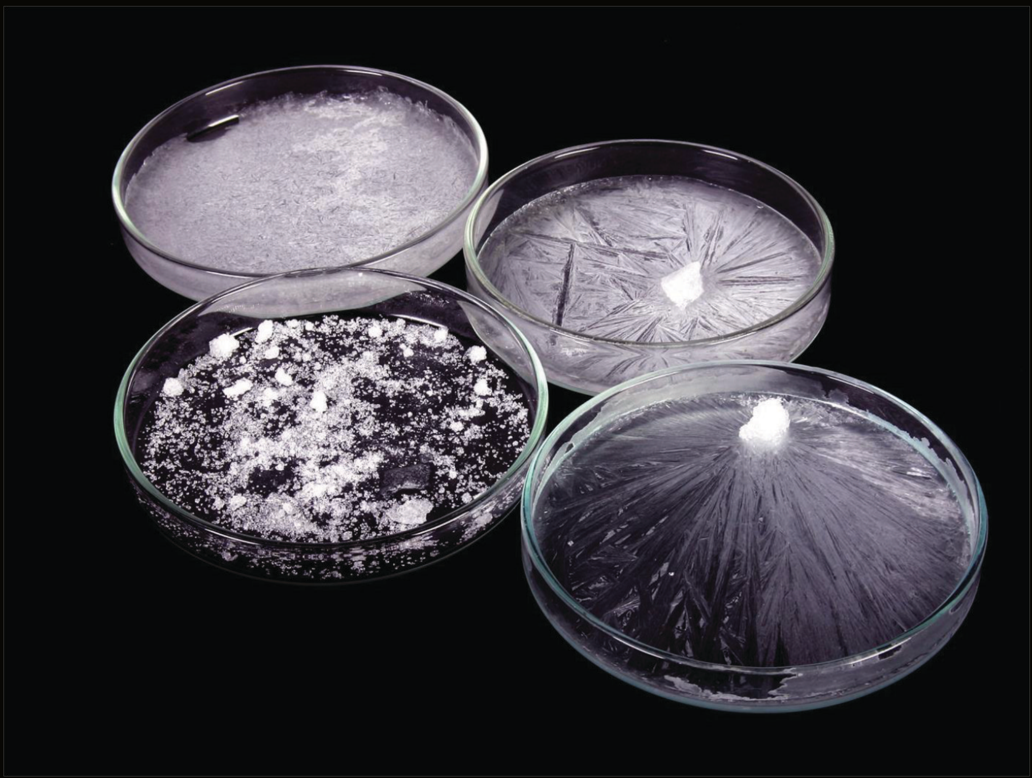
Credal Networks as Computational Analogues

These ontological ideas have a clear counterpart in contemporary methods for reasoning under uncertainty, especially in cases where classical probabilistic assumptions break down. Standard Bayesian reasoning assigns precise numerical probabilities to hypotheses and updates them by conditionalisation, but it presupposes well-defined prior probabilities and trustworthy likelihoods—assumptions that often fail in complex, data-sparse, or noisy scientific settings (Walley 1991).

Imprecise probability theory tackles this limitation by replacing single probability values with credal sets: sets of probability distributions that are all compatible with the available evidence. Instead of betting on one precise number, credal sets record epistemic indeterminacy as a structured range of admissible values, avoiding spurious precision while maintaining formal rigour (Walley 1991). Credal networks generalise Bayesian networks by assigning credal sets to nodes and propagating lower and upper probability bounds through the network, so that inference delivers conclusions that are robust across all admissible distributions. When new evidence arrives, it reshapes the network as a whole, jointly adjusting dependency relations and admissible ranges.

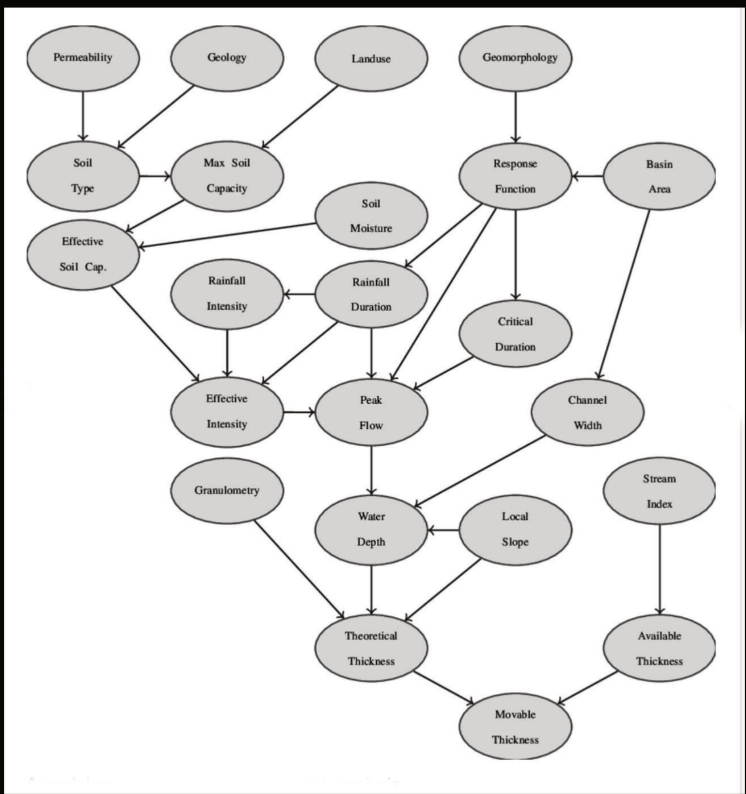
This kind of global yet internal reorganisation parallels Simondon's notion of transduction: local evidential perturbations spread through the inferential structure, generating new equilibria while preserving certain stable inferential relations. Those preserved relations play a role analogous to Poincaré's enduring mathematical structures, where what survives theory change is not a fixed ontology but a resilient relational core (Poincaré 1905; Simondon 2009).

Within this framework, constitutive conventions appear as epistemic constraints that delimit which belief structures count as admissible. They shape inference not by fixing particular outcomes, but by bounding the space of rational belief; when evidential pressures overwhelm these constraints, the result is a structural reorganisation of the credal architecture—an epistemic counterpart to Simondonian transductive individuation.



Above: *Crystallisation of sodium acetate - Taki Jo - https://edu.rsc.org/feature/fractional-crystallisation/3007561.article*

Below: *A credal network for environmental risk analysis - https://www.researchgate.net/figure/A-credal-network-for-environmental-risk-analysis_fig3_267020133*



In complex AI systems, this means that learning under uncertainty can be understood not as a sequence of isolated updates, but as the continual reshaping of an underlying inferential structure that must remain workable even as it changes—epistemic structure in motion in a computational sense.

Conclusion

Poincaré's structural epistemology safeguards rational scientific progress not by fixing what the world is ultimately made of, but by tracking how relational structures are preserved and reshaped over time, even if the mechanisms of that reshaping remain in need of further clarification (Poincaré 1905). Milena Ivanova makes this vision explicit in her three-tier model, showing how stability and change can coexist without appeal to absolute foundations (Ivanova 2015).

Drawing on Gilbert Simondon's ontology of individuation, this essay has tentatively extended that framework by reinterpreting epistemic structure as a metastable field of becoming—formed through tension, only provisionally stabilised, and transformed through transduction (Simondon 2009). Credal networks provide a computational analogue of this dynamic, showing how epistemic systems can adapt under uncertainty while preserving robust inferential relations, and offering a setting in which the transduction metaphor can be tested rather than simply asserted (Walley 1991).

In an era marked by complexity, noisy data, and adaptive models, Poincaré's framework therefore looks newly relevant—not as mere historical curiosity, but as guiding architecture for contemporary epistemic practice. The broader implication is that epistemic structures—scientific paradigms, theoretical frameworks, even cognitive schemas—are neither rigid nor arbitrary, but processual stabilisations: temporary resolutions of tension that make inquiry possible while remaining open to reconfiguration.

On this view, anomalies and disruptions are not signs of failure, but occasions for renewed individuation and prompts to ask whether the ontological and mathematical tools in play genuinely illuminate the dynamics at stake. Poincaré's enduring contribution lies in seeing that structure is not opposed to change but its very condition; conceived as structure in motion, epistemic architecture becomes the medium through which scientific knowledge can be at once resilient and transformable without abandoning the capacity for critical self-revision (Poincaré 1905; Friedman 2001).

References

Friedman, M. (2001) The Dynamics of Reason. Stanford, CA: CSLI Publications.

Ivanova, M. (2015) ‘Conventionalism, structuralism and neo-Kantianism in Poincaré’s philosophy of science’, Studies in History and Philosophy of Modern Physics, 52, pp. 114–122

Poincaré, H. (1952) Science and Hypothesis. New York: Dover Publications. (Originally published 1905.)

Sangalli, M., de Campos, C. and Krak, T. (2025) ‘Conservative inference in credal chains using belief functions’, [Journal name], [volume(issue)], pp. [page range].

Walley, P. (1991) Statistical Reasoning with Imprecise Probabilities. London: Chapman and Hall.