22 Narrative and Natural Language

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Abstract
The distinction that has become standard between natural language and formal language, which rests on differentiating what is socially evolved and experiential from what is purposefully planned, suggests that a similar emphasis on experientiality may illuminate the distinction between narrative and formal modes of knowing, which figures prominently in this volume. Support for that perspective comes from developments in both narratology and computational linguistics. A key concept from both specialties – and for this volume – is that of 'scripts', which indicates how even texts that are explicitly formal may be understood as narratives by experienced readers. An explicit example that illuminates these themes comes from James Clerk Maxwell's classic paper 'On Faraday's Lines of Force'. It juxtaposes narrative and formal modes of representation and displays their relative advantages, suggesting that the development of scientific knowledge often depends on continual feedback between natural narrative and formal analysis.

22.1 Introduction

The chapters in this volume all respond to the question, what work does narrative do for practitioners in the sciences? For many authors their answer involves a distinction between narrative modes of knowing and formal modes, even when their aim is to undermine the distinction as a dichotomy. A clear statement appears in Paula Olmos's reassessment of the meaning of *just-so stories*. She seeks a middle way between the attempt to subsume phenomena under the skeleton of formal, lawlike, causal explanations and the fleshed out narrative treatment of 'a complex, highly contextual and somewhat indeterministic causal web' (Olmos, Chapter 21). The qualities of narrative that seem strongest here and throughout the volume include its capacity to capture subtlety, ambiguity, complexity, pattern, temporality, contingency, counterfactuals and, perhaps most centrally, colligation (Morgan, Chapter 1). Formality is weak in these capacities. Its strength lies in simplification, precision, rigour, unification and logic. But why

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does the distinction between what counts as narrative and what counts as formal seem so commonsensical to so many of us, as though it requires no accounting? Is there not something quite straightforward behind it?[1]

22.2 Natural Language is Evolutionary and Experiential

I take my cue initially from Thomas Piketty whose 1,000-page best-seller *Capitalism and Ideology* (2020) has received widespread acclaim. It is a professional economist's analysis of how income inequality has developed over the past 200 years, based on a massive amount of data assembled from many countries, emphasizing their diverse histories and the multidimensionality of current choices. In methodological remarks 'on the complementarity of natural language and mathematical language', Piketty asserts that such an undertaking has necessarily required that he rely primarily on natural language, for 'there is no substitute for natural language when it comes to expressing social identities or defining political ideologies' (Piketty 2020: 43).

Piketty's appeal to natural language is at the same time an appeal to narrative. It opens the way for him to write economic analysis as narrative history and to make extensive use of literary depictions to give an accurate sense of economic conditions as lived experience. Jane Austen's *Sense and Sensibility*, for example, provides a real-life sense of how capitalism operated around 1800 and what it meant in personal and social terms for a gentrified family in straitened circumstances to have an income from investment capital of 100 pounds a year rather than 4,000 pounds (Piketty 2020: 15, 170).

The great lesson, of course, is that 'Those who believe that we will one day be able to rely on a mathematical formula, algorithm, or econometric model to determine the "socially optimal" level of inequality are destined to be disappointed'. Only natural language, and thus narrative understanding, 'can promise the level of nuance and subtlety necessary to make choices of such magnitude'. Nevertheless, Piketty also relies heavily on formal language, 'the language of mathematics, statistical series, graphs, and tables', which fill many pages and are equally indispensable for social and political reflection (Piketty 2020: 43).

Taking this hint from Piketty, I want to suggest that we think of the easy distinction between narrative and formal as reflecting the distinction as now commonly formulated between natural and formal language. A natural language – also a human or ordinary language – is a naturally evolved product of practical use and repetition. Similarly, a native speaker acquires the capacity for

[1] Although a number of chapters in this volume use 'narrative' in the sense once standard among narratologists of an unfolding in time of a causally connected sequence of events, I will use it here in the broader sense of an unfolding of a representation or interpretation, without any necessary reference to temporality but prioritizing experientiality, as in more recent 'natural narratology' (n. 2).

its subtle usage, and thus for the qualities we typically associate with narrative, through many years of lived experience, including sensory experience. In contrast, formal languages – mathematics, logic, programming languages, technical vocabularies – are purposefully designed and purposefully developed, rather than socially and informally evolved. Arguably, there are no native speakers of formal languages, which has much to do with their limited capacity for narrative. But it is easy to overdo this rather static emphasis, since formal languages do develop over time and their experienced readers do inflect them with narrative characteristics.

The experiential perspective on natural language resonates strongly with the recent turn in narratology to 'natural narrative', following the seminal work of Monika Fludernik (1996).[2] 'Natural' here refers to the grounding of narrative in lived experience, so that narrativity is virtually identical with 'experientiality'. Fludernik's model has the advantage of decoupling the concept of narrative from the traditional plot-based requirements of temporal progression and causal connectedness. It also highlights the experience of the reader, and not only the author, in producing the narrativity of a text (Caracciolo 2014). This text–reader interaction will figure importantly below with respect to 'scripts'.

The significance of natural language and natural narrative being interconnected through experientiality finds ready expression in Brian Hurwitz's lovely paper on epistemic switching in medical narratives (Chapter 17). Focusing on their narrative features, he regularly emphasizes the tension between the 'personal experiential' character of medical anecdotes and the 'more formal, impersonal' nature of clinical case reports. 'Unlike case reports, which have become highly regulated medical accounts, anecdotes remain informally patrolled schema, cast in a vernacular language that has less recourse to technical and formal terminology than cases' (Hurwitz, Chapter 17). This is not to say, however, that anecdotes have had little role in medical knowledge. Although much maligned at times as subjective and untrustworthy, they have continued to occupy a prominent place in medical reasoning.

Querying how that happens, Hurwitz highlights another important aspect of the narrative/formal distinction: the 'epistemic switch' that occurs when anecdotal testimony of personal experience gets 'revoiced' as evidence. He offers the striking example of how Pfizer chemists almost serendipitously took up the experience of a few miners who sheepishly reported that a potential medication they were taking in a clinical trial seemed to produce erections. Through

[2] My thanks to Kim Hajek for calling my attention to natural narratology and for discussion of the issues involved. For the purposes of this essay I am ignoring the possible problem that, with respect to language, natural is opposed to formal while, with respect to narrative, natural is sometimes opposed to unnatural (meaning impossible in the real world) rather than simply non-narrative. Fludernik casts doubt on the natural/unnatural distinction.

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quantification and standardization in a much larger trial the chemists transformed the rather undefined substance with anomalous side effects into a fully medicalized treatment for erectile dysfunction (sildenafil). 'The miners' natural language testimonies came to be revoiced in the "de-anecdotalized" formal language of Pfizer's subsequent trial participants [. . .] expressed in datapoints', thereby according them objective, scientific status (Hurwitz, Chapter 17). The change in language, from natural to formal, was at the same time a change in speakers and in context, producing an epistemic switch that transformed the very meaning of the miners' testimonies.[3]

22.3 Computational Linguistics

Issues of this kind have taken on new relevance and have led to an explosion of research and development in relation to natural language processing (NLP) and the more sophisticated expectations for natural language generation (NLG) and ultimately natural language understanding (NLU) using artificial intelligence. The questions that arise in this area exhibit so many parallels to those of the present volume that it should perhaps come as no surprise that one commercial company has taken on the same name: 'Narrative Science'. The company specializes in NLG, meaning that its programs convert business data into narrative form, so it advertises itself as 'a data storytelling company, creating products that turn business data into plain-English stories' (Narrative Science 2020).

At the simplest level, NLP has shown considerable success in extracting from narrative texts specific data items that are readable in formal computer programming languages. For example, massive digitization of medical records has made it imperative to be able to extract from patient histories contained in clinical notes and pathology reports the sorts of specific information that would be helpful for continuing care. One study from 2012 looked for temporal expressions of time, date, duration, and sets of these expressions in narrative records of 33,000 individuals. Judged against trained human reviewers, the success rate was a respectable 83 per cent. Still, the false positives and negatives are instructive for just how limited such programs still are. The phrase 'capsule may be opened and sprinkled on applesauce' produced a spurious categorization of 'date', while 'diarrhea daily for about 1–2 months' failed to produce a 'duration' (Reeves et al. 2012). Another NLP study from 2014, using key word searches to extract data, was able to document a striking lack of continuity in the narrative records of patients moving from inpatient to outpatient care and suffering from 'post-intensive care syndrome'. At the same

[3] See Paskins (Chapter 13), for an excellent exploration of the epistemic issues involved in shifting between narrative (thick) and formal (thin) language.

time, it showed the severe limitations of its own capabilities, misidentifying the word 'depressed' (mental state) with 'depressed ejection fraction' (heart function) (Sjoding and Liu 2016: 1444).

What makes such attempts at natural language processing so interesting for the reflections on narrative and formal knowledge in this volume is just how difficult it is to formulate in programming language the sorts of subtle distinctions in natural language that humans recognize without thinking. That difficulty reinforces the tendency among many observers to essentialize the narrative/formal distinction as a matter of two dichotomous modes of comprehension. This response may be particularly pressing in the context of computer science education. A thought-provoking paper on priorities in the teaching of programming and assessment of skills stresses that there are 'two quite different mental processes' and summarizes the problem as follows:

- For a formal language, a single and complete meaning is contained entirely within the text, and the understanding process consists of determining that meaning from a close analysis of the text alone.
- For a natural language, an analysis of the text is only part of the task, as this may produce multiple possible meanings. A particular meaning can only be derived by making use of available contextual information for disambiguation. (Cutts et al. 2014: sect. 3)

The authors therefore argue that the two sorts of comprehension should be kept strictly apart, for otherwise confusion will reign. So-called pseudo-code, which blends formal and natural languages and is intended to be used 'for human understanding of algorithms rather than machine understanding' is, according to this view, problematic at best, at least for novices. Interestingly, the authors acknowledge that experienced programmers, reading past ambiguities in the pseudo-code, 'will be able to infer exactly what is meant'. If so, one wonders, then why not teach those skills in the first place and explore with budding programmers how to relate them to machine language?

That is in fact the goal of the sophisticated field of computational linguistics: 'the scientific and engineering discipline concerned with understanding written and spoken language from a computational perspective, and building artefacts [software] that usefully process and produce language' (Schubert 2020: preface). While specialists' views differ on language as a mirror of mind, they agree on the goal of building linguistically competent computers and on the fact that the project faces a myriad of intractable hurdles. Most telling is that natural language is ambiguous at all levels of syntax, semantics and pragmatics and depends for its understanding on a vast store of contextual and world knowledge (or background knowledge).[4] But, given the facility that humans have in

[4] On the further issue of value differences expressed in computerized representations, see Dick (Chapter 15).

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disambiguating natural language, some analysts have argued that what might be called their narrative or colligatory skills ‘more nearly resemble fitting the observed texts or utterances to familiar patterns’ than solving complex logical problems (Schubert 2020: sect. 2.4, 5.4).

22.4 Scripts

One early approach of this kind was pioneered by Roger Schank and Philip Abelson, who recognized that understanding and inference in natural language were heavily dependent not simply on a large store of background knowledge but on patterns of belief and expectation that they called ‘scripts’ (Schank and Abelson 1977). Scripts are ‘the prototypical ways in which familiar kinds of complex events [. . .] unfold’ (Schubert 2020: sect. 1.2, 4.2). Implementing this perspective in the formal language of machines remains elusive – pattern recognition in general being a notoriously difficult problem – but it caught the interest of people outside computational linguistics, including the well-known cognitive narratologist David Herman (1997: 1047–1048). And that brings me back to the present volume.

In her illuminating chapter, ‘Reading Mathematical Proofs as Narratives’ (Chapter 19), Line Andersen presents an empirical study of how mathematicians read proofs as narratives. This seems surprising since we normally think of proofs as epitomizing the rigour of formal language and at the farthest remove from narrative. But mathematicians, it turns out, do not necessarily read proofs in a line by line checking of the logical argument being presented. Instead, reading a proof as a telling of how something happened, they often narrativize it by drawing on their own experiential background knowledge, recognizing whole sections of a proof mimetically as the familiar patterns that Schank called scripts. These sections they can skim over and fill in from the scripts. Less familiar parts may throw up surprises, which require close attention and may lead to new scripts. In this way, mathematicians can come to *understand* proofs by reading them as narratives (Andersen, Chapter 19).

To put this a bit differently, a mathematician’s understanding of a proof, on Andersen’s account, offers an excellent opportunity to reflect on how the experientiality of ‘natural narrative’ needs to be interrelated with that of ‘natural language’. Reading a proof in experiential terms changes what looks to an outsider like a purely formal structure into a natural narrative for the reader; so too the experiential reading enriches the formal language of rigorous proof with the natural language of narrative, for it calls up meanings that the unaided formal language, lacking background and context, cannot convey. On the other hand, without its formal language the proof would not be a proof. This is the sort of conundrum that bedevils computational linguistics. It is meat and potatoes, however, for the narrative science of this volume.

Similar examples from the volume illuminate the point in additional ways. Nina Kranke, in 'The Trees' Tale: Filigreed Phylogenetic Trees and Integrated Narratives' (Chapter 10), argues that phylogenetic tree diagrams, which accompany texts written in the formal language of molecular biology and computer-assisted analysis, are produced and read by biologists as visual narratives of evolutionary history. She observes that biologists very often do not read the entire text of a paper but that 'the informed reader understands the central argument of the paper just by looking at the diagram'. In thus 'reading' the text/diagram, they fill in from their own background knowledge, in the manner of scripts and of natural narrative, much information that is not actually present in the text or even the diagram itself. In this, Kranke's biologists do their reading much like Andersen's mathematicians. But the diagrams introduce an even stronger element of text–reader interaction – one that is perhaps more typical of narrative science – for they are created in the first place not simply as formal diagrams but as visual narratives that already express the author's experience and aim to evoke the experience of the reader. The images of real animals sometimes placed at strategic locations on the more formal diagrams seem to announce this sought-for interaction. Finally, reading the diagrams as visual narratives highlights the sensory character of much natural language.[5]

Yet another aspect of the importance of scripts appears in Andrew Hopkins's discussion, 'The Narrative Nature of Geology and the Rewriting of the Stac Fada Story' (Chapter 4). Hopkins argues that a geologist, in habitually reading professional papers as temporal narratives rather than the non-temporal descriptions they appear to be, relies on an array of scripts that 'derives from a geologist's specific training and experience' and arises in conversation. This emphasis on training and informal communication signals that the scripts are a community affair. Indeed, how could they not be since the natural language of experts is socially evolved as well.

22.5 Narrative and Formal Juxtaposed: A Historical Case

As is apparent already from the chapters in this volume referenced above, it is common to see works in the sciences that employ both narrative and formal modes of knowing, but it is unusual to see the two approaches set side by side and treated quite separately in a single work, thus highlighting their comparison. One such example, however, comes from a canonical paper of James Clerk Maxwell, 'On Faraday's Lines of Force' (Maxwell 1855).[6] Because Maxwell

[5] A similar script-like interpretation may apply to the formalized 'storm cards' discussed by Bhattacharyya (Chapter 8).

[6] The discussion below is adapted from Wise (2021), which compares the theories of 'lines of force' and 'action at a distance' in terms of the narrative qualities that make them believable. See references there to illuminating discussions of Maxwell's method of physical analogy.

reflected deeply on the significance of the natural (from 'nature') and the formal ('mathematical') for what he regarded as different 'minds', I will attempt in what follows to extract from his example both a clear expression of the differences and what we might take away from his discussion of their relation.

Published in 1855, 'Faraday's Lines' was Maxwell's first contribution to what was becoming British electromagnetic field theory. In it he took up Michael Faraday's long-running experimental study of electric and magnetic action, which Faraday treated as a mediated action taking place through fields of force in the space surrounding electric or magnetic materials, rather than as the direct unmediated action known as 'action at a distance' (like Newtonian gravitational force). Wilhelm Weber in Germany, working in the action at a distance tradition, had already unified all known phenomena of electromagnetism in a single mathematical formula. It expressed the force acting directly between two electrical particles simply in terms of their distance apart and their relative velocity and acceleration. Faraday instead represented electrical and magnetic phenomena in terms of 'lines of force' distributed in space with an accompanying 'electrotonic state', but just how to conceive the lines of force and the electrotonic state remained rather nebulous and he had no mathematical account of their action.

That is where Maxwell entered the picture. In well-known lines, he expressed his attitude to the two theoretical perspectives of Faraday and Weber: one in the natural language of narrative and the other in formal mathematical language.

> What is the use then of imagining an electro-tonic state of which we have no distinctly physical conception, instead of a formula of attraction which we can readily understand? I would answer, that 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. (Maxwell 1855: 208)

That is the attitude towards the narrative and the formal that informs Maxwell's own representations of Faraday's theory in two quite different ways.

Narrative representation. Maxwell devoted the first half of his long paper to what he famously called a 'physical analogy' between Faraday's lines of force and fluid flow lines, asking his reader to 'consider these curves not as mere lines, but as fine tubes of variable section carrying an incompressible fluid' (Maxwell 1855: 158). Beginning from this simple verbal image, available to anyone who had watched water flowing down a drain, he gradually unfolded a three-dimensional picture of a space full of flowing fluid, including velocity distribution, sources and sinks, a resisting medium, pressure gradients, and changes in the properties of the fluid. The entire account required only the simplest of mathematical relations, remaining almost entirely within the realm of natural language and common imagination.

In elaborating on the virtues of this physical analogy, Maxwell remarked that ‘my aim has been to present the mathematical ideas to the mind in an *embodied* form, as systems of lines and surfaces and not as *mere symbols*, which neither convey the same ideas, nor readily adapt themselves to the phenomena to be explained’ (Maxwell 1855: 156, 187; emphasis added). In the concept of embodied ideas, he here prefigured a critical concept of natural narratology. Embodiment, Fludernik emphasizes, ‘evokes all the parameters of a real-life schema of existence [. . .] and the motivational and experiential aspects of human actionality likewise relate to the knowledge about one’s physical presence in the world’ (Fludernik 1996: 30; Caracciolo 2014: sect. 2). Similarly, by embodied mathematics Maxwell did not mean simply that he was giving a physical exemplification of an underlying and more fundamental mathematical structure. It was physical understanding he was after and that did not inhere in ‘mere symbols’.

Embodiment here has a literal significance that Maxwell expressed repeatedly through his life. As he would put it in his ‘Address to the Mathematical and Physical Sections of the British Association’, in 1870: ‘[many physicists] calculate the forces with which the heavenly bodies pull at one another and they feel their own muscles straining with the effort. To such men momentum, energy, mass are not mere abstract expressions of the results of scientific inquiry. They are words of power, which stir their souls like the memories of childhood’ (Maxwell 1870: 220). This highly sensory and emotional aspect of embodiment helps to illuminate Maxwell’s presentation of Faraday’s lines in narrative form. It was grounded in experience and memory, both conceptual and sensory, and preserved the ‘vividness’ and ‘fertility’ of such experience.

It may be helpful also to recognize that Maxwell’s presentation of lines of force was explicitly a fictional narrative in which the flowing fluid was an imaginary substance. ‘It is not even a hypothetical fluid which is introduced to explain actual phenomena. It is merely a collection of imaginary properties which may be employed for establishing certain theorems in pure mathematics in a way more intelligible to many minds and more applicable to physical problems than that in which algebraic symbols alone are used’ (Maxwell 1855: 160).

Having established his basic image in familiar verbal terms, Maxwell employed it to draw together nearly all of the phenomena of electricity and magnetism as conceived by Faraday, including the distribution of magnetic lines around a magnet (Figure 22.1) and the equivalent distribution of magnetic lines produced by electric currents, or electromagnetism. The existence of

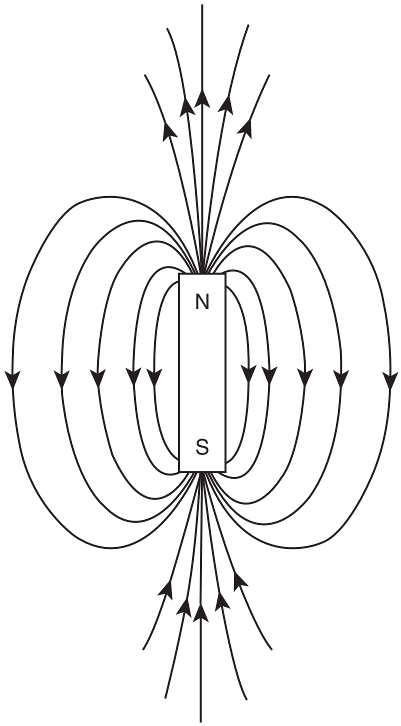

Figure 22.1 **A representation of lines of force surrounding a bar magnet with north and south poles**

electromagnetism meant that electric current lines and magnetic lines, each conceived separately in terms of flow, had to be interrelated dynamically. Their qualitative relation can be readily understood pictorially with reference to a coil of wire carrying a current (Figure 22.2a), which behaves like a bar magnet with north and south poles, and produces an equivalent distribution of magnetic lines (compare Figure 22.1).

The pattern of the magnetic distribution by itself can be seen as a dynamic balance, which Faraday described as resulting from a tendency of each magnetic line to *contract* along its length and for adjacent lines to *repel* each other laterally. But these effects in the magnetic lines are mirrored reciprocally in the electric lines by the tendency of each electric line (or turn in the coil) to *extend* along its length and for adjacent lines to *attract* laterally. He depicted the reciprocity visually as in Figure 22.2b (Faraday 1855: para. 3265 and plate IV, fig. 1).

Always pursuing the unity of natural powers, Faraday had said of these linked rings and their dynamic balance that it ‘probably points to the intimate physical

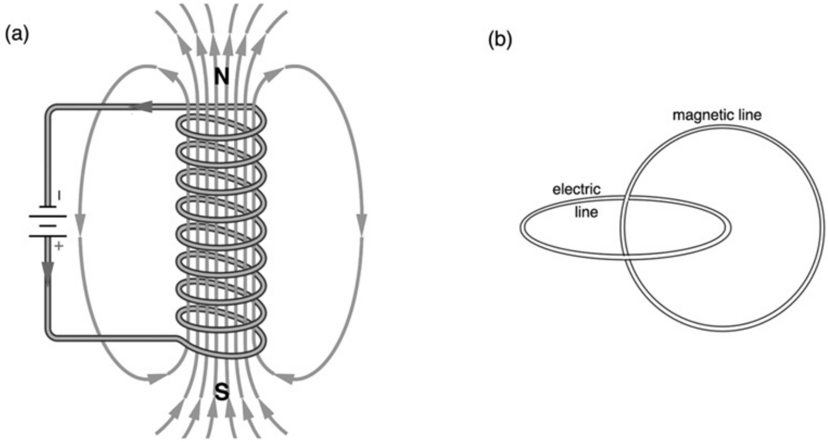

Figure 22.2 (a) and (b) **Current-carrying coil and Faraday's depiction of the relation of electric current lines**
(a) current-carrying coil (dark lines) behaves like a bar magnet. (b) Faraday's depiction of the relation of electric current lines and magnetic lines, which Maxwell called a 'mutual embrace'.

relation, and it may be, to the oneness of condition of that which is apparently two powers or forms of power, electric and magnetic' (Faraday 1855: para. 3268). Maxwell agreed, but with his flair for evoking sensory perception, he labelled their relation a 'mutual embrace' of electricity and magnetism (Maxwell 1855: 184, 194 n.).[7] The importance of this heuristic image can be seen in the fact that it would guide his theorizing through successive versions until he reached his mature theory. For the moment, however, the analogy of lines of force as lines of fluid flow provided no understanding of what the reciprocal dynamics of magnetic and electric lines might consist in physically.

Formal representation. Failing in his quest to understand the mutual embrace physically, Maxwell took up in the second half of his paper an abstract mathematical approach, although still one in which the embrace held a central place. From Faraday and from the flow analogy he had available for mathematical expression the concepts of flow velocity and pressure gradient at any point, or 'quantity' and 'intensity' of flow, which provided his starting point. The reciprocal dynamics of the mutual embrace suggested

[7] For Maxwell's continuing use of the metaphor in later papers, see Wise (1979).

further that just as the *quantity* of current passing through a surface surrounded by a magnetic line could be expressed in terms of the *intensity* in the magnetic line, so the *quantity* of magnetic force passing through a surface enclosed by a current line should be expressible in terms of the current's *intensity*. But no such relation of magnetic quantity to current intensity existed experimentally, which is why the mutual embrace remained a suggestive image, an ambiguous symbol of what one might hope to realize physically.

This ambiguity was particularly troubling for Faraday's great discovery of electromagnetic induction, whereby an increase or decrease of the magnetic quantity passing through a surface surrounded by a closed conductor would induce a current in the conductor. Like Faraday, Maxwell thought there must be some corresponding physical condition in the conductor, an 'electrotonic state', whose changing intensity would correspond to the current produced. If so, then this hypothetical electrotonic state might also serve to complete the reciprocal dynamics of the mutual embrace.

Utilizing known laws of electric currents and known theorems of partial differential equations, Maxwell developed his abstract theory of the electrotonic state in a set of six interrelated laws. For the sake of 'seeing' what this formal structure looked like – simply as a formal object – it may be useful to write down four of the laws in modern vector notation, noting three parts (Figure 22.3).

By incorporating the electrotonic state $\mathbf{I}_o$ in this set of equations Maxwell was able to give beautifully coherent expression in the second set of laws to the dynamics of the mutual embrace (electromagnetism) and in the final law to the production of currents in a changing magnetic field (electromagnetic induction). But what was the electrotonic state? It remained a mysterious stranger physically and experimentally. As he put it, 'I have endeavoured to express the idea which I believe to be the mathematical foundation of the modes of thought indicated in [Faraday's] *Experimental Researches*. I do not think that it contains even the shadow of a true physical theory; in fact, its chief merit as a temporary instrument of research is that it does not, even in appearance, *account for* anything' (Maxwell 1855: 207).

22.6 Feedback between Narrative and Formal Representations

In Maxwell's seminal paper, we see juxtaposed two very different representations of the mutual embrace of electric and magnetic lines of force. The first is a narrative unfolding in natural language of a physical analogy, leading to a visual image of the embracing lines and a verbal description of their

1. Two laws (from the flow analogy) expressed the proportionality of quantity ***Q*** and intensity ***I*** in each system of lines of force, electric and magnetic,

$$\mathbf{Q}_e \propto \mathbf{I}_e$$

$$\mathbf{Q}_m \propto \mathbf{I}_m$$

2. Two more laws expressed a newly conceived reciprocity in the mutual embrace, now written in terms of the supposed electrotonic state. The total magnetic quantity $\boldsymbol{Q}_m$ passing through a surface is given by the electrotonic intensity $\boldsymbol{I}_o$ summed around its edge,

$$\iint \mathbf{Q}_m \cdot \mathrm{d}\,\boldsymbol{\sigma} = \oint \mathbf{I}_o \cdot \mathrm{d}\,\boldsymbol{\lambda}$$

And reciprocally, the total electric quantity $\boldsymbol{Q}_e$ passing through a surface is given by the magnetic intensity summed around its edge,

$$\iint \mathbf{Q}_e \cdot \mathrm{d}\,\boldsymbol{\sigma} = \oint \mathbf{I}_m \cdot \mathrm{d}\,\boldsymbol{\lambda}$$

3. A final law stated that the electric intensity at any point in a conductor is proportional to the rate of change of the electrotonic state at that point.

Figure 22.3 **Maxwell's abstract theory of the electrotonic state**

dynamics. The second is an abstract structure in formal mathematical language, having no necessary relation to the physical analogy. The two sharply contrasting modes of representation are reminiscent not only of the difficulties computational linguists face in their attempts to relate natural language to machine language but of the 'epistemic switch' that Brian Hurwitz observes for the way in which anecdotal knowledge gets 'revoiced' as medical knowledge. They have different meanings in their very different contexts and do not translate one into the other. It was in reference to this sort of epistemic difference that Maxwell remarked that 'mere symbols', in contrast to an embodied analogy, 'neither convey the same ideas, nor readily adapt themselves to the phenomena to be explained'. Reflecting in his 1870 'Address to the Mathematical and Physical Sections' on how fundamental the difference is, he ascribed it to different minds. 'There are [. . .] some minds which can go on contemplating with satisfaction pure quantities presented to the eye by symbols, and to the

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mind in a form which none but mathematicians can conceive'. But there are other minds which 'are not content unless they can project their whole physical energies into the scene which they conjure up' (Maxwell 1870: 220).[8] To put that in the terms I am pursuing here, the formal language of the mathematical representation would be poorly described as a 'translation' from the natural language of the physical analogy. For they are different modes of knowing based on different kinds of experience. This key point about experience deserves some development.

With respect to the embodied physical analogy, its creative power depended entirely, both for Maxwell and his readers, on their prior experience of fluid flow – indeed, on their own embodiment and sensory experience – on what natural narratologists call experientiality and on what the linguists call contextual and world knowledge. In his narrative representation this experiential character is explicit. That goes to the heart of the productive work narrative commonly does for scientists, as we see throughout this volume. In contrast, when Maxwell formalized the mutual embrace within a mathematical structure by introducing the electrotonic state, both the embrace and the state were abstracted from physical experience and became mathematical objects defined by the structure. As such they did not, 'even in appearance, account for anything'. Instead, they became well-defined mathematical objects, or, better, mathematical possibilities seeking experimental and conceptual realization. Such creations are of course critically important in the sciences, although as formal representations there is nothing explicitly experiential or narrative-like about them.

But we should not go too fast here and suppose that understanding Maxwell's formal structure was independent of experience. Instead, looking not at the formal laws but at his derivation of them raises the issue of experience in a different manner. The derivation consists in 15 pages of carefully orchestrated mathematical reasoning based on known relations in electromagnetism and known mathematical theorems, known to Maxwell specifically through his friends William Thomson and George Stokes. For him, then, the derivation reflected his personal experience with the mathematics involved, even though that experientiality did not – and could not – appear in the formal language of the text. Similarly, as Line Andersen has made us aware, any reader who shared large portions of that prior knowledge and could therefore see the developing pattern of the derivation might replace much of it with their own experience in getting to the resulting laws. That is, the knowledgeable reader, relying on familiar 'scripts', would read the derivation – and would understand it – more

8 Maxwell inserted an intermediate type who preferred visualization in geometrical forms, drawn or imagined.

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like a natural narrative of how the results emerged than as an exercise in logic and would only question the logic if it seemed problematic. Narrativity, it seems, is difficult to escape.

These reflections lead me to a final question about how we should think more generally of the relation between the more narrative and the more formal aspects of scientific reasoning. Are they epistemically different modes of knowing? The refractory character of overcoming the natural/formal distinction in computational linguistics suggests that they are. Maxwell's juxtaposition of narrative and formal representations of the mutual embrace offers a rather stark example to reinforce that view. On the other hand, many of the chapters in this volume show that narrative and formal aspects are not so easily separable and that both play highly creative roles. So again, how should we think of the relation?

Paula Olmos argues for an 'integrative approach'. She cites Sharon Crasnow in support of the view that 'causal links or mechanisms are *better* understood [. . .] under a narrative rendering than under the crystallized mode of a formal formula'. She also cites Adrian Currie and Kim Sterelny for the view that 'narrative approaches should *combine* with the virtues and benefits of formal models' (Olmos, Chapter 21; Crasnow 2017; Currie and Sterelny 2017). Crasnow's approach might suggest that narratives subsume the formal while Currie and Sterelny's approach would suggest complementarity. Both subsumption and complementarity have attractive qualities, as the cited papers themselves so well attest.

Subsumption would imply that formal modes of knowledge are reductions or abstractions from narrative modes, which are more primitive (in the sense of prior and more basic) and more general. Maxwell made just this point in critiquing the view characteristic of mathematical minds. For them, 'the physical nature of [a] quantity is subordinated to its mathematical form', but this point of view 'stands second to the physical aspect in order of time, because the human mind, in order to conceive of different kinds of quantities, must have them presented to it by nature' (Maxwell 1870: 218). The reduction from nature, or from lived experience, would account for why it is so difficult to encompass the subtleties of natural language in formal language, or why natural language understanding remains rudimentary while natural language generation is making significant strides.

Complementarity, on the other hand, would suggest that neither mode has epistemic priority (at least as a practical matter of use if not a developmental one). They are so distinct that they do not overlap significantly but sit side by side. Once again, Maxwell put it succinctly in terms of modes of knowing: 'For the sake of persons of these different types, scientific truth should be presented in different forms, and should be regarded as equally scientific, whether it appears in the robust form and the vivid colouring of a physical illustration, or in the tenuity and paleness of a symbolical expression' (Maxwell 1870: 220). Thomas Piketty, with whose expression of the complementarity of natural and formal language I began, similarly reminds us of this 'paleness' of mathematical econometric models in comparison with the 'vivid colouring' of narrative history, as well as of the need for both. (See also Paskins, Chapter 13, on 'thin' and 'thick'.)

It seems that Maxwell believed both that formal truths develop as abstractions from narrative truths and that the two are complementary. If he was right then we need a model that encompasses both. Such a model might be found in feedback, in the view that scientists are typically shifting back and forth between narrative and formal modes of representation in a continuous feedback loop, in which each stimulates the other and in which the mutual stimulation is a source of development.[9] From a relatively primitive natural conception an initial formal representation is abstracted, which suggests a more elaborate natural conception, and so on. Maxwell seems to have intended that understanding when he wrote: 'If the skill of the mathematician has enabled the experimentalist [physicist] to see that the quantities which he has measured are connected by necessary relations, the discoveries of physics have revealed to the mathematician new forms of quantities which he could never have imagined for himself' (Maxwell 1870: 218). A bit more history will support that feedback reading for Maxwell's own work.

Prior to 'Faraday's Lines' of 1855, Maxwell had immersed himself in both the narrative papers of Michael Faraday and the mathematical papers of Thomson, who had himself been mathematizing Faraday, with a flow analogy and with Faraday's support. So an ongoing dialectic was already in full swing in the letters that passed between, first, Thomson and Faraday, and then Maxwell and Thomson. It would continue in the series of papers that Maxwell subsequently published, pursuing both more adequate physical analogies and more complete mathematical structures. Already in 1855 he left his reader with the hope that an extended physical analogy would someday complete the picture of electromagnetism with an electrotonic state. 'By a careful study of the laws of elastic solids and of the motions of viscous fluids, I hope to discover a method of forming a mechanical conception of this electro-tonic state adapted to general reasoning' (Maxwell 1855: 188).

Famously, although physical analogies continued to stimulate mathematical formulations, neither Maxwell nor any of the others who tried would find an adequate mechanical conception of an etherial medium in space that would

[9] See also Meunier (Chapter 12) on the view that when objects of research, or 'epistemic things', become stabilized the more fluid research narratives drop out.

fully meet the need. Equally famously, as the physical analogies became ever more problematic, the formal structure became ever more dominant, until Heinrich Hertz, discoverer of electromagnetic waves in 1887, famously remarked that 'Maxwell's theory is Maxwell's Equations'. But for Maxwell himself, who had died in 1879, this state of things could only have been temporary. 'We are probably ignorant even of the name of the science which will be developed out of the materials we are now collecting, when the great philosopher next after Faraday makes his appearance' (Maxwell 1873: 360).[10]

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