What happens when we intervene?

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> "A truth is solely constituted by rupturing with the order which supports it, never as an effect of that order."
>
> Alain Badiou, *Being and Event* (2005): xii

> "As a field, artificial intelligence has always been on the border of respectability, and therefore on the border of crackpottery. Many critics... have urged that we are over the border.... On the other hand, in private we have been justifiably proud of our willingness to explore weird ideas, because pursuing them is the only way to make progress."
>
> Drew McDermott, "Artificial intelligence meets natural stupidity" (1976): 4

1. Background

This lecture is a spinoff from asking what it might be like to reason with a fully realised artificial intelligence.[1] By 'fully realised' I mean an AI designed to be 'intelligent' in its own terms rather than by the yardstick of what is sadly thought to be a fixed human attribute.[2] That question has led me to ponder our current relation to digital machinery and its outputs, and so to ask what happens when we intervene to form new knowledge with these outputs. And behind all of this is an ongoing project of mine to explore how investigations in other areas than our own can help us form a computing that is *of* rather than merely *in* the humanities – whatever good service it may be doing these disciplines at the moment.

The digital machinery we have, in all its various forms, mostly serves our pre-existing interests and habits. No surprise there. But what if we were to open up the machine's alien qualities, looking for difference rather than always polishing the mirror? What if the machine were to us not merely a 'life companion',[3] like the mobile phone, but also capable of revealing a recalcitrant stranger? What if we regarded its strangeness and defamiliarising potential as the point?

Investigating this potential means not only plunging below the surface of the interface into the logic of hardware to find out what sort of a tool we have. It also means turning to those other areas of research that have been long in pursuit of other ways of reasoning – for reasoning has both a history and a geography.[4] I have in mind cross-culturally adept fields like anthropology, even cross-species fields like ethology. Here, drawing on anthropology, I propose to prepare for and at the end briefly ponder the best example I know: divination.

2. The promise

By convention we assign the beginning of digital computing to Alan Turing's invention of a machine that is *abstract*, *mathematical* and *universal*. More than 80 years of a complicated history lies between it and the implementations we have. Yet those originating three qualities still lead to unresolved questions. Marvin Minsky, Herbert Simon and others have pointed out that the physical instantiation of Turing's device gave the word 'machine' a new meaning – but what meaning is that?[5] If, as many think, the computer is a mathematical device, what sort of mathematics does it implement, and what significance does this mathematics have for scholarship? Turing meant 'universal' in a technical sense, but the quite astonishing adaptability of his abstraction has persuaded many to think that it is a plan for realising virtually anything. So we ask, what can it *not* implement?

Our fixation on the *golem*-potential of the machine would seem to follow, attested by the re-labelling of Turing "imitation *game*" as the 'Turing *Test*' – a term he seemed careful to avoid (Whitby 1996), for 'test' implies the expectation that the machine will *become* us. We know from Robin Gandy that Turing's aim was mischievously provocative: Gandy recalls him reading portions of "Computing machinery and intelligence" aloud "always with a smile, sometimes with a giggle" (Gandy 1996: 125). Turing wanted us to *pay attention*: isn't intelligence a *question* to be investigated, as research coming out of ethology and cognitive science tells us, rather than a fixed benchmark, final answer or solution?

We may seem to be already a good way along toward conversation with my algorithmic stranger when we regard the trading off of comfortably familiar close-reading for the somewhat unfamiliar (if not disturbing) scope of distant-reading, with its statistical charts that allow us, in a sense, to comprehend a whole corpus of literature. But, all too quickly, life with charts becomes familiar. The lover of charts will stay with them, regarding text as a way of sharpening the tool; the lover of literature will return to the poetry, prose or drama from the digital overview the charts provide and regard the technologically enabled detour as just that, however enlightening it may be. Habituation, Viktor Shklovsky pointed out, devours everything (Shklovsky 1991/1917: 12).

But what if we took up our tools not only as applications of idea or method X, serving the agenda of discipline W, to object Y? What if we thought also of these tools *not* (as Margaret Masterman once suggested) telescopes of the mind showing new things out there and new details of old ones already catalogued? (Masterman 1962) What if we designed and built tools for something like anthropological fieldwork into the strange culture of the digital? What if we saw them, in Polish artist Bruno Schulz's terms, as works of art – not portraits of the known but harbingers, "probes sunk into the nameless", perpetually *in statu nascendi,* 'in the process of being born'? (McCarty 2009)

If, as I believe, knowledge is inseparable from the way it is made, stabilised, transmitted and communicated, then what we learn from computing an object is not just a stepwise improvement but also, potentially, something new and fundamentally different, changing as computing develops. Neuropsychologist Michael Anderson argues that new tools reveal new properties of the world "that actually *require* these tools to perceive them accurately" (Anderson 2012: 181f). I would go further. I would say, at least sometimes we require these tools to perceive those properties at all – even to make them real.[6] I put it to you that the potential realised by favouring the other-directed over the mimetic qualities of the machine is to go beyond the sharper focus on our objects of interest and greater comprehension of them. My point is perspectival and ontological: by refracting an object computationally, we can see *a different it*.

3. Intellectual weed-control

But first three impediments to deal with.

First is the fading doctrine that we reason internally by means of cognitive surrogates, i.e. with 'knowledge representations' of real world objects.[7] To be sure, we *compute* with representations as an integral part of the overall process I am about to describe, but we don't ourselves reason that way. The formerly dominant model in cognitive science – I'd say, the distorted image of cognition reflected back from the machine that instantiates it – says that we do.[8] The counter-argument has been gathering strength, in active development from the 1960s in the psychology of affordances, neurophysiology of perception, artificial life, AI and robotics.[9] But no time for all that. I must simply ask you to assume that we have embodied, 'supersized' minds which think in and with the world around us.

The second impediment is the reductive and dismissive just-a-tool mindset, which misleads by obscuring experience with tools (ask an articulate craftsman)[10] and so blinding us to the difference between digital and non-digital kinds of intelligence. Simply put, a tool is 'just a tool' only in the hands of an incompetent, who for lack of skill cannot perceive *with* and *from* it.

Interface transparency is the third, closely related impediment. It is essentially the notion that the digital nature of the machine is irrelevant because it is entirely an intermediate, internal matter, created by analog-to-digital 'signal conditioning' on input and converted back into continuous form on output.[11] Others regard 'digital' to be hardly worth notice because of its assimilated ubiquity. Indeed, we can and often do ignore the digitality of digital productions and appliances. But we have little hope of understanding the research potential of the machine without taking the discrete mathematical logic of hardware and its effects on our reasoning into account. Two innately digital processes are at issue: first, what I call the axioms of digitising – *complete explicitness* and *absolute consistency* of representation; second, the way in which the digital machine enacts the code it is given. I will amplify and argue much of this as I proceed. But note: I am *not* arguing from necessity; I *am* arguing for potential we can choose to realise.

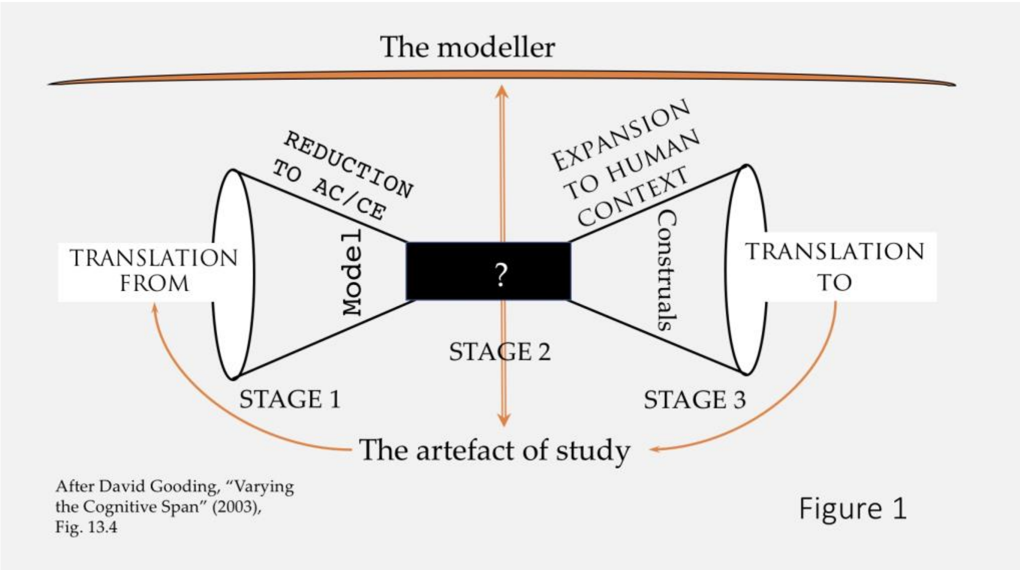


Figure 1

4. The big computational picture

Figure 1 is a rough sketch of the whole process, adapted from the historian and philosopher of science David Gooding. He argues that when we compute we vary our "cognitive span", first reducing it to algorithmic size for the combinatorial and calculational advantages algorithms confer, then expanding it back to human dimensions.[12] Gooding's crucial point centres on the sense-making at the end of the process, i.e. the forming of new knowledge out of what he calls *construals*, "flexible, quasi-linguistic messengers between the perceptual and the conceptual" (Gooding 1986). I will return to this sense-making intervention later. But you will already have grasped that Gooding's diagram is essentially a portrait of modelling in three stages: (1) digitisation on the left, (2) computation in the middle and (3) construal on the right.

Now, since *nothing* gets to be computed that has not been shrunk to algorithmic size, the computationally tractable 'form' is in effect forcibly parted from the intractable, hermeneutic 'content'. By obeying the same axioms of digitisation, metalinguistic markup offers manual translation of the hermeneutic into the computable. As the

Text Encoding Initiative has conclusively demonstrated, this workaround is of immense utility wherever agreement can be reached temporarily to ignore (in Hayden White's memorable phrase) "the content of the form" (White 1987). What we do then is preserve significance in the mind or by other means, and all else computation leaves behind, for Stage 3. Stage 2 is all about sorting, counting and calculating the formal data *without respect to its temporarily suspended potential to signify*. In other words, meaning is there at the beginning, before computation, at stage 1; it returns at the end, when the interpreter construes knowledge from the results, at stage 3; but it is *irrelevant* inside the machine, at stage 2. In the 17th Century, Leibniz articulated the operative principle; he called it *cogitatio caeca* ("blind thought").[13]

Leibniz's first publication was the *De arte combinatoria* (1666), which used blind thought in a scheme to compute all possible thoughts from a set of conceptual primitives.[14] What the recombinatorial potential of the machine offers us is different: not closure on truth, which the theology of Leibniz's time and place offered, but unforeseen or unforeseeable possibilities of interpretation, created stochastically at Stage 2. Thus mathematician Martin Gardner: "When ideas are combined in all possible ways, the new combinations start the mind thinking along novel channels and one is led to discover fresh truths and arguments."[15]

5. X-raying the black box, step 1

I call Stage 2 a 'black box', first because in all but trivial cases we cannot know how the computation specified by software is actually carried out;[16] and second because we lack (as far as I know) easily accessible explanation of how intelligent things can be carried to intelligible conclusions by a necessarily thought-blind digital process.

In the reception history of the digital machine, two exaggerated reactions are commonplace: on the one hand, unqualified assertions of a machine that 'thinks'; on the other, denials that thinking in any sense can be posited of a device that can only do what it is told.[17] Evidently the same polarisation of opinion accompanied news of Charles Babbage's Analytical Engine in the mid 19th Century. Since then many who have been troubled by the claim of intelligent machinery have reached back to Lady Ada Lovelace's view in 1843 that,

> The Analytical Engine has no pretensions whatever to *originate* any thing. It can do whatever we *know how to order it* to perform. It can *follow* analysis; but it has no power of *anticipating* any analytical relations or truths. Its province is to assist us in making *available* what we are already acquainted with. (Lovelace 1843: 721)

But unlike almost all of those who have quoted or paraphrased her, she did not stop there. Babbage's Engine, she went on to say in a Leibnizian spirit,

> is likely to exert an *indirect* and reciprocal influence on science itself in another manner. For, in so distributing and combining the truths and the formulae of analysis, that they may become most easily and rapidly amenable to the mechanical combinations of the engine, the relations and the nature of many subjects in that science are necessarily thrown into new lights, and more profoundly investigated. This is a decidedly indirect, and a somewhat *speculative*, consequence of such an invention. (721, 723)

In his 1950 paper on intelligence, Turing quoted her first two sentences, agreeing with Douglas Hartree that she had left open the possibility of an intelligent machine (Turing 1950: 450). Turing observed that the Analytical Engine had the potential to be such a machine but for want of memory and speed. What I want you to note is Lady Ada's glimpse of the intelligence of which such a machine is in principle capable, namely the kind produced in large part by the "mechanical combinations" it blindly enables. So also John von Neumann, who a century later, in a paper on the theory of automata, noted of the Engine's digital successor that it is by design a combinatorial device (von Neumann 1951: 16), that is, essentially a machine which reckons by sorting, counting and doing simple arithmetic, though in complex ways at great speed. AlphaGo Zero is its current apotheosis.

Thus the basics of what can be done by sorting and counting comprise the first step in x-raying the black box of computation. But before I go further, I want briefly to touch on the history and anthropology of the mathematics involved, namely the science or art (opinions differ) of finding configurations in a finite number of elements under given constraints.

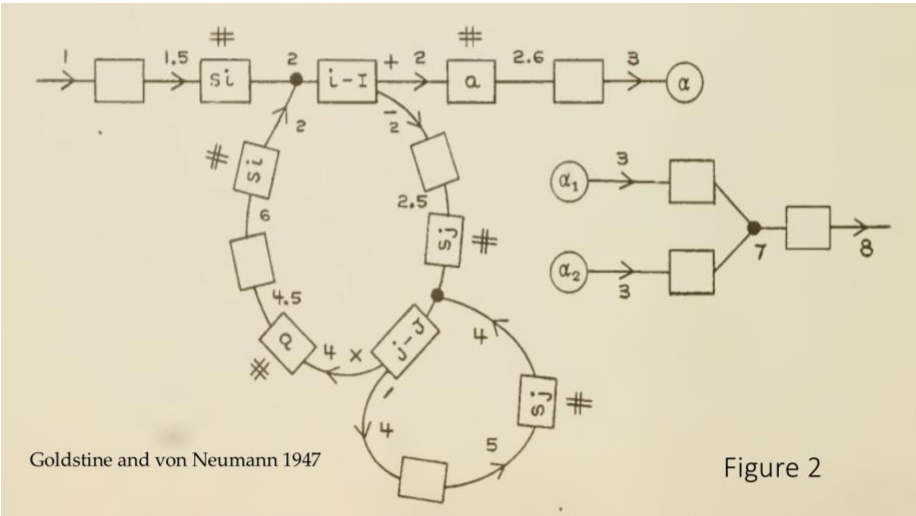
Mathematicians and computer scientists call the field *combinatorics*.[18] But as G.E.R. Lloyd has pointed out for 'mathematics' across cultures and historical periods, there is a danger that by adopting the single term we come to view quite distinct varieties as primitive or deviant anticipations of a modern science (Lloyd 2009). So also for 'combinatorics'. All I can say in this brief compass is that recent scholarship has brought a host of combinatorial practices into prominence and raised the question of why this vigorous and diverse field of activities was not given its fair due in the past.[19] Class bias is one such reason, for it is decidedly demotic; preference for cultivation of the mind over commerce and daily necessities, where it has flowered for millennia, is another.[20] For Christian Europe the very close relation of combinatorics with gambling, divination and other forms of competition for authority surely didn't help.[21] It seems no accident that the inclination to reconsider combinatorial ways of reckoning has come with the enabling spread of the combinatorial machine. (Note: I am not arguing cause-and-effect, rather, at most, mutual reinforcement.)

The demotic character of combinatorics, rooted in sorting and counting, made it a species of what came to be called 'mixed mathematics', in which mathematical reasoning is embodied in and arises from subjects of physical interest.[22] Francis Bacon's distinction of 'mixed' from 'pure' mathematics at the beginning of the 17th Century,[23] followed by D'Alembert in Diderot's *Encyclopédie*, cleared a space for combinatorics in taxonomies of learning. Nevertheless the notion that purity in mathematics fostered divine contemplation persisted.[24] By the beginning of the last century combinatorics found itself largely relegated to "the slums of mathematics" (Kleitman 2000: 124). Then the mid-century development of digital computing gave its practitioners just the engine they needed.[25]

6. X-raying the black box, step 2

The second step in x-raying the computational black box is to peer into the logical implications of its hardware architecture. The best sources for this are from the early period in the history of the digital machine, during which basic discoveries and decisions were being made, their implications thought through and explained to colleagues, before consensus and implementation put them beyond active discussion. Particularly valuable, then, is Herman Goldstine's and von Neumann's 1947 report, "Planning and Coding of Problems for an Electronic Computing Instrument" – the first attempt we know to work out what programming would entail.[26] Its key statement is this:

> Since coding is not a static process of translation, but rather the technique of providing a dynamic background to control the automatic evolution of a meaning, it has to be viewed as a logical problem and one that represents a new branch of formal logics. (Goldstine and von Neumann 1947: 2)



They go on to explain this "dynamic background" by highlighting two basic features of the hardware (which make the crucial difference between pre-computational and computational senses of 'machine'): its provisions, on the fly, for conditional sequencing of instructions and for self-modifying code. Conditional sequencing, illustrated by one of their 'flow diagrams' in Figure 2, means that the default order in which instructions are executed can be changed by the result of a calculation or other external condition – hence the 'jump' and recursive 'loop', and later the 'interrupt'.[27] Self-modifying code is made possible by storing instructions and data in the same memory-space, subject to the same manipulations, thus 'code as data'. Self-modification, a basic property of AI programming languages, became especially important when in the 1970s researchers turned to evolutionary biology for help with the basic problem of learning how to learn (a.k.a., 'machine learning'), hence the 'genetic algorithm', and the 'genetic programming' which has followed it.[28]

A striking consequence is that prediction of exactly how a computational process unfolds is impossible.[29] Thus, again, the 'black box'. Indeed, the box is made even blacker by the unpredictability of the errors intrinsic to any physical machine. Because of this, von Neumann argued, these errors should be treated "not as an extraneous and misdirected or misdirecting accident, but *as an essential part of the process under consideration*" and understood as we understand the complex flow of energy in a thermodynamic system.[30] This is hardly what we usually think of as 'mechanical'; rather it is computation as a turbulent stream of energy flowing through a constraining channel. Furthermore, correctness is ruled out of court from the get-go by the nature of modelling, which is necessarily selective and blind to whatever the modeller does not or cannot know.[31]

All this puts us quite far from the abstract, timeless, error-free logic of Boolean algebra. Extravagant hardware and software engineering supports a robust *illusion* of inexorable logic all the way down; in reality this "engineered disciplining" gives us, within the constraints of its discrete mathematics, an indefinitely malleable arena for playing games (some of them quite serious, of course).[32] To borrow Oulipian mathematician Claude Berge's metaphor for combinatorics,[33] it gives us the structure (he imagines a desk drawer) in which a number of objects may be configured, counted and described any number of times. That we cannot tell in detail how it does what it does directs our attention to the channelling of the data by the constraints we set, i.e. to modelling, and to the sense-making to which I about to turn.

I have asked, "What happens when we intervene?", deliberately echoing philosopher Ian Hacking's argument in *Representing and Intervening* (1983) that theoretical entities in the physical sciences become real when we learn how to manipulate them. The scholar seems to be in a different predicament than the scientist, who in the typical account operates on objects Western science has by convention sundered from his or her thoughts, feelings and other contingent circumstances (Keller 1996). The scholar operates within the blurry region between, as Gooding wrote, the perceptual and the conceptual. (Actually, so does the experimental scientist, but that's a story I haven't time to tell.[34]) My question, then, would seem to be one for the cognitive sciences, particularly cognitive psychology.

But because we lack data analogous to the laboratory notebooks Gooding studied, I turn as promised to an area of research where analogous problems have been considered.

7. Re-contextualising the question

In 1957 the cognitive psychologist Jerome Bruner observed that when we run into the limits of our knowledge we respond by "going beyond the information given… beyond evidence, to fill in gaps, to extrapolate", producing "interesting combinations of ideas before their worth is known. [What we do] precedes proof…. It is founded on a kind of *combinatorial playfulness*…"[35]

However intuition works out of sight, in the ultimate privacy of one's mind,[36] Bruner's memorable suggestion puts my argument for reasoning in the world, with the machine, in a nutshell: to rephrase slightly, that the machine propels us beyond the data by providing means to play with the data combinatorially. At the time Bruner wrote, computation seemed to offer cognitive psychologists just the language they needed to articulate their nascent theories;[37] as a result, combinatorics became a well-known figure of thought in psychology.[38] But, I think it fair to say, what they were theorising was not *the* mind but a semi-computational model of mind – at one remove from both machine and mind, and so a suggestive model of what happens when we intervene.

Again, to understand this semi-computational, semi-cognitive state we need studies which focus on the process of coming to know rather than on the knowledge made. But I take a different tack here, wanting to ask how others have used combinatorial play with devices – machinery, if you will – to get beyond their "information given". To quote historian of Greek religion Walter Burkert on divination, I want to ask, how have others in the past, and not only in the European tradition, devised "a way of extending the realm of human *ratio* into areas that it cannot usually penetrate" (Burkert 2005: 30), and thus have seen beyond their given predicaments?

Divination is among the richest and most complex of examples. Its practices are ancient and pervasive. Historically, in the European tradition, institutions competing with it for authority have for centuries relegated divination to the shadows, just as combinatorial maths was relegated. Like combinatorics, numerous studies during the last few decades have brought much of it into the light for further enquiry. Nevertheless, it remains a perilous subject to address, not only because of a formidable amount of scholarship. Our inclination to see the past and others in our own terms; the historical and cultural variability of "the metaphysics of chance" (Hacking 2006/1975: 56); and the uncertainty of the evidence we have are but three severe difficulties.[39] Here I take the risk, but I must restrict myself to the briefest explanation of why I think divination is important for a greater understanding of what the machine can do.

The key point of contact between divination and computation is unsurprisingly their technical procedures for discovering the otherwise unknown or unknowable by manipulating configurations of objects, whether tangible or electronic. In divination, such objects as knucklebones, dice, coins or the milfoil stalks of the *Yijing* are used to produce an unpredictable (we say, 'random') result.[40] Of the essence, it seems, is to guarantee a response which is presumed to speak to the question asked but is otherwise autonomous, therefore unaffected by the special interests of those involved. *How* it speaks to the question may not be immediately intelligible, as reports on the oracular pronouncements of the Sibylline oracles and consultations of the *Yijing* demonstrate. Long pondering and/or expert interpretation may be required.

Divination, Peter Struck observes, is "the most robust ancient version in a long series of attempts" to get a grip on knowledge which somehow comes (we say 'intuitively') "by ways other than self-conscious, goal-directed, inferential chains of thought".[41] It is an attempt systematically and reliably to reach sources of such knowledge, not necessarily codified or consistent but internally coherent and procedural. Noticing these attributes, recent studies have argued that divination is a rational mode of enquiry, which is to say, a *differently* rational mode undertaken for *different* ends than ones familiar to most of us.[42] Hence, in each case, we must ask Jean-Pierre Vernant's questions: What kind of rationality? How does it function within its social context? (Vernant 1991/1974: 303)

A first reaction to all this may be to leap from disbelief to scorn. We have all had enough of hype. But the link between computational enquiry and oracular consultation has been in the air if not obvious from the beginning of digital machinery.[43]

Take, for example, the 1950 advertisement in Figure 3, below, of a Sibylline figure seated atop IBM World Headquarters in Manhattan, passers-by astir with excitement over the massive computer visible in the front windows from 1948 until 1952. Yes, the commercial motivation is clear. But why *this* particular iconography? We do not know what the artist, Rolf Klep, had in mind,[44] but we can see the care with which he appears to have summoned ancient Greek divination, alluding to the Delphic Sibyl by way of Michelangelo's "Delphica", perhaps inflected by Rolf's spill of printout to allude to other Renaissance depictions of the Sibyls, such as Pinturicchio's fresco of the prophet Hosea and the Delphic Sibyl for the Borgia Apartments in the Vatican (1492-4).[45]

Figure 3

The pictorial analogy is to my mind clear: as we are to the machine, so the ancient Greeks (and other clients of diviners) were and are to their oracles. But as with all analogies, this one is not a statement but a question, not an equivalence but a relation to be mined and its ore tested. And it is emphatically *not* a relation of our superior understanding to their superstitious belief.

In his discussion of "ancient divination between enigma and epiphany" Burkert concludes with the epiphanic. For the people of the ancient Mediterranean, he wrote,

> to wait for the birds and to observe them flying, to wait for lightning to flash, a meteor to fall, or even to listen to the rustling leaves of the tree at Dodona or to look for reflections in Didyma's water meant to get out of a closed, egocentric system, to get into touch with "otherness," with the whole environment, to experience the all-embracing net of existence, nay universal *sympatheia*, expecting the unexpected. (Burkert 2005: 48)

Kurt Vonnegut, in *Cat's Cradle*, called it "dancing lessons from God".

On the other hand, scepticism was and is justified as counterweight (though not negation): such moments of opening up are evanescent; oracular pronouncements are often in need of interpretation and so are vulnerable to the reintroduction of special interests. Cognitive scientist Andy Clark, for example, has recently argued that the brain is a "predictive engine" which allows us to 'surf uncertainty', as he puts it, by anticipating what's coming before it arrives (Clark 2016). This is crucial to our survival but at the same time conditions us to get what we expect. Hence, I reply, the crucial difference made by the carefully staged but unpredictable *swerve*. Good sceptics that we are, we try the unexpected for cognitive toxicity then, if it passes our test, take it in and begin to change. Yes, this is modelling once again, but with a difference. We really do not know where it is going. It is conversational, improvisational, generative, emergent. And that is why a fully realised artificial intelligence is so important.

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[1] This reference is to McCarty (forthcoming) delivered for the workshop "Science in the Forest, Science in the Past", organised by G.E.R. Lloyd (Darwin College, Cambridge), Aparecida Vilaça (Museu Nacional, UFRJ, Brazil), Mauro Almeida (Unicamp, São Paulo) and Manuela Carneiro da Cunha (USP, São Paulo and University of Chicago, USA) and held at the Needham Research Institute (Cambridge), 31 July to 2 June 2017. I am enormously indebted to Lloyd and to Tim Smithers for their encouragement and critical suggestions for this lecture.

[2] For the kind of *technical* trajectory I am thinking about, see Silver *et al* 2017, Hassabis 2017. Tim Smithers has pointed out that AI systems embody and exhibit very different kinds of 'intelligence' (or whatever we wish to call it) according to their design (private e-mail, 27/6/18).

[3] Samsung's announcement for the Galaxy S4 mobile phone was, "A Life Companion for a Richer, Simpler and Fuller Life", perhaps taken from the popular song, "Be my life's companion" (1951), written by Bob Hilliard and Milton De Lugg. Cf. Wilks 2010.

[4] Struck 2016: 13-16 and esp. Lloyd 2018.

[5] Simon 1977/1960: 67; for Minsky's remark, McCorduck 1979: 71.

[6] Hacking 1983: 22-4, 262-75; Scarry 1996.

[7] Davis, Shrobe and Szolovits 1993; Sowa 2000.

[8] Pylyshyn 1980; cf Anderson 2014: xix, 17-19.

[9] Anderson 2003 and 2014. See also Gibson 1966 and 1986/1977; Steels and Brooks 1995; Agre 1997; Pfeifer and Bongard 2007 (esp. Brooks' Preface); Krois, Rosengren, Steidele and Westerkamp 2007; Clark 2008 and the History of Distributed Cognition Project, http://www.hdc.ed.ac.uk/, including Clark's "The Extended Mind" lecture, http://www.hdc.ed.ac.uk/seminars/extended-mind (10/7/18); Chemero 2009; Shapiro 2011 and 2014; Barrett 2011; Malafouris 2013. Embodied cognition, engaged and co-formative with the world in which it occurs, is crucial for understanding the role of manipulatory interaction in construing knowledge from computation, at which I can only hint in this lecture.

[10] Polanyi 1983; Ingold 2013 and 2000, Part III.

[11] Smith 2005; contra, Evens 2015. On the electronics, see Horowitz and Hill 2015, Chapters 1 and 10, and the definition in the Preface to Newby 1994: "*signal conditioning* is… the manipulation of a voltage or current waveform into a more useful or manageable size or shape or its undergoing a logical or mathematical operation."

[12] Gooding 2003; see also 1990.

[13] Dascal 1987: 43; see also Tunstall 2011; Pasini 1997; Picon 2008; Rutherford 2006: 243-4.

[14] Dascal 2008 and 1997; Knobloch 1974; Couturat 1914/1901. For the background in a broad historical sweep see Eco 1995/1993; for an introduction Gray 2017. For Ramon Llull, under the influence of whose philosophy Leibniz was working then, see Rossi 2006/1983 and Johnston 1987.

[15] Gardner 1958: 17. See esp. Stuart Kauffman's combinatorial idea of the "adjacent possible" in Kauffman 2000: 142-57, 207-9 and *passim*.

[16] See 'black box' in von Neumann 1951 and 1956.

[17] On the computer as capable of thought, Simon and Newell 1958; as a 'giant brain', Anon. 1947; Berkeley 1961/1949; as a 'moron' see McCorduck 1979: 128, 159f (where Lovelace is mentioned), 173; Andree 1958: 2, 106; Gaskell 1957: 562; Bowles 1967: 213-20.

[18] Poincaré 2004/1908; Polya 1966; Rota 1969; Berge 1971/1968: 1-11; Biggs 1979; Kleitman 2000. See also Hacking 2014: 76-8.

[19] For the history overall see Robson and Stedall 2009, Wilson and Watkins 2013; for Europe, Goldstine, Gray and Ritter 1996; Biggs, Lloyd and Wilson 1995; Knobloch 1974 and 1979; ancient Greece, Netz 2009; China, Bréard 2010; Islam, Selin 2016: 230-2, 1385-88, 2302-4; Hebrew, Selin 2016: 174, 187.

[20] Asper 2009; Lloyd 2009: 9-12; Netz 2009. For “class bias” Hacking 2014: 138f.
[21] Ore 1953; David 1962; Klingshirn 2005.
[22] Dear 2011; Epple, Kjeldsen and Siegmund-Schultze 2013; Gaukroger and Schuster 2002; Brown 1991; Netz 1999: 60f; Hacking 2014; Barrow 1734: 11f, 20f.
[23] Bacon 1674/1605: 109-11 (Book III, Chapter VI).
[24] Moritz 1914 gives numerous examples of mathematical rapture. On pure vs applied see Ulam 1969: 2; Kline 1972: 3.1036-8; Rota 1978: 26. On pure mathematics, Hardy 1940 and T. W. Körner’s Foreword to Hardy 2008: v-xi.
[25] Note von Neumann’s argument for the vital connection of mathematics to its empirical wellspring, necessitating its “rejuvenating return to the source…[in] more or less directly empirical ideas.” (von Neumann 2004: 184)
[26] See the previous report, Burks, Goldstine and von Neumann 1946: 4-7, 33-7; also Goldstine 1972: 255-60; Aspray 1990: 63-72; Campbell-Kelly and Aspray 1996: 91-7.
[27] Goldstine and von Neumann use the term ‘induction’ for the loop (II.i.86-7), showing the pervasive inclination to fit computing processes to human cognition.
[28] See Holland 1975; Booker, Forrest, Mitchell and Riolo 2005; Poli, Langdon and McPhee 2008. See also Miettinen, Neittaanmaki, Mäkelä and Périaux 1999; Koza 1992.
[29] Setting instructions directly in the hardware and stepping through them manually allowed this, indeed was once the only possibility. But no machine we are likely to have available allows this now. We can write carefully in machine code to guarantee a one-to-one correspondence between the programmer’s intention and the machine’s action, but doing so would serve no reasonable purpose.
[30] von Neumann 1951: 17 and Wittgenstein 2009: 83-4 (§193); von Neumann 1956: 43 (my emphasis), citing Shannon’s application of thermodynamics to information theory.
[31] Smith 1985; McCarty 2014/2005; Morgan 2012.
[32] I’m indebted to Alan Blackwell for the idea of *extravagant* engineering and to Tim Smithers for “engineered disciplining”.
[33] I have left the Ouvoir de Littérature Potentielle (Oulipo) out of my discussion of combinatorial activities for want of space. Oulipo’s, especially Italo Calvino’s and Georges Perec’s, development of the Lucretian *clinamen* tells basically the same story of liberation so does not change my argument substantially, although it provides an important connection with 20th-century literature and literary theory. See Motte 1986 for an introduction. For Calvino see esp. his “Cybernetics and ghosts” (in Calvino 1986/1980) and “Prose and anticombinatorics” (in Motte 1986); on Calvino, Duncan 2012, Harris 1990 and Pilz 2005.
[34] From Hacking 1983 onward the experimental sciences have received long-needed attention as autonomous ways of doing science; see Gooding 1990 for a detailed case study.
[35] Bruner 2006/1957: 22 (my emphasis), 2007/1960: 51, also 1977/1960: 60 and Auyoung 2013: 64.
[36] See Lisa Osbeck’s and Barbara Held’s introductory overview and the collected papers in Osbeck and Held 2014, esp Part II.
[37] George Miller in Baars 1986: 218f; Miller, Galanter and Pribram 1960.
[38] Piaget and Inhelder 1975/1951; Inhelder and Piaget 1958/1955; Inhelder and Chipman 1976; Fischbein 1975, chapter 7, also 6 and 8; and note Simon 1962. For combinatorics in Bruner, see in addition Bruner 2006/1957 and 1979.
[39] Johnston 2003 discusses these for the case of Roman sortition.
[40] On the use of dice (*astragaloi*) in ancient Greek divination, see Johnston 2008: 99 and Graf 2005; on Roman sortition, Johnston 2003; on *Yijing* divination Smith 1991: 19-21, 108-112, Raphals 2013: 128-31, 166-73.
[41] Struck 2016: 15f, 31, 250.
[42] The work of G.E.R. Lloyd is especially important; see e.g. Lloyd 2002, Chapter 2, and Lloyd 2018; Burkert 2005; Struck 2016; Johnston and Struck 2005. Note Struck’s comment on studies of Greek divination that, “Collectively, the main contribution of this area of scholarship has been to work through the powerful observation that rationality has a history, and to show the gains we realize by a

deeper understanding of cultures whose notions of it are not always isomorphic to our own." (Struck 2016: 13f.

[43] The term 'oracle' is not infrequently applied to the digital machine in the early period, anticipated by Turing, who casually refers to "some unspecified means of solving number theoretic problems, a kind of oracle as it were" in his PhD dissertation (1938: 13); he does not develop the metaphor. Hodges 2014/1983: 240 cites Secret Service Officer F. W. Winterbotham's account on seeing the Bombes at Bletchley Park: "early in 1940 I was ushered with great solemnity into the shrine where stood a bronze-coloured column surmounted by a larger circular bronze-coloured face, like some Eastern Goddess who was destined to become the oracle of Bletchley, at least when she felt like it. She was an awesome piece of magic." (Winterbotham 1974: 33-4; see also 51, 130, 198, 223, 268). Mathematician and computer scientist John Kemeny notes that "For the first two decades of the existence of high-speed computers… man approached the computer the way an ancient Greek approached an oracle." (Kemeny 1972: 21) The ORACLE (Oak Ridge Automatic Computer and Logical Engine) was the name given to one of three machines following the lead of von Neumann's Institute of Advanced Study machine (Aspray 1990: 56, 91f) See also Janlert 1987; Jones 2016: 66f.

[44] The closest we can get to Klep's history is the short biography in Baldinger 1969, which shows him to be a man of wide artistic and cultural interests and documents his post-WWII travels, including to Italy.

[45] The "Oracle on 57th Street" is reproduced by permission of Shell Brands International AG (Switzerland). Michelangelo's fresco is in the public domain. For Pinturicchio's search e.g. for 'Pinturicchio Sibyl Borgia'.