The Computational Roots of Hyper-Causality
Newton onwards - overarching aim of science became the extraction of the computable causal content of the world ... theories which computably predict, capturing truth via proofs ...

Einstein [p.54, `Out of My Later Years', 1950]: “When we say that we understand a group of natural phenomena, we mean that we have found a constructive theory which embraces them.”

Computability versus descriptions

but even more ...
... I would like to state a theorem which at present cannot be based upon anything more than upon a faith in the simplicity, i.e. intelligibility, of nature ... nature is so constituted that it is possible logically to lay down such strongly determined laws that within these laws only rationally completely determined constants occur (not constants, therefore, whose numerical value could be changed without destroying the theory) ...
Strong Determinism

[According to Strong Determinism] ... all the complication, variety and apparent randomness that we see all about us, as well as the precise physical laws, are all exact and unambiguous consequences of one single coherent mathematical structure.

1936 - Turing’s machines arrive

Points to a model of computational natural processes within structures which are countably presented.

But - techniques for presenting machines give the Universal Turing machine - and emergence of incomputable objects.
Emergence in the Real World ...

- Growth of **Chaos theory**, generation of informational complexity via very simple rules, accompanied by the emergence of new regularities - e.g. Robert Shaw’s dripping tap [1984]

- **Link** between structures in nature, and mathematical objects, such as the Mandelbrot and Julia sets

- Penrose, Smale - **computability** of Mandelbrot, Julia sets?
Now we witnessed ... a certain extraordinarily complicated looking set, namely the Mandelbrot set. Although the rules which provide its definition are surprisingly simple, the set itself exhibits an endless variety of highly elaborate structures.


A mathematical example of emergent structure
1950s - Alan Turing proposes a simple reaction-diffusion system describing chemical reactions and diffusion to account for morphogenesis, i.e., the development of form and shape in biological systems.

See [http://www.swintons.net/jonathan/turing.htm](http://www.swintons.net/jonathan/turing.htm)
Chaos, Order & Self-Organisation

- **SYNERGETICS** - the study of the origins and evolution of macroscopic patterns and spacio-temporal structures in interactive systems

- Emphasis on mapping out self-organisational processes in science and the humanities - e.g. autopoiesis

- Mathematical modelling of nonlinear and irreversible processes, dissipative structures ...

Emergence is often invoked in an almost mystical sense regarding the capabilities of behavior-based systems. Emergent behavior implies a holistic capability where the sum is considerably greater than its parts. It is true that what occurs in a behavior-based system is often a surprise to the system's designer, but does the surprise come because of a shortcoming of the analysis of the constituent behavioral building blocks and their coordination, or because of something else?

"... the characteristic behaviour of the whole ... could not, even in theory, be deduced from the most complete knowledge of the behaviour of its components ... This ... is what I understand by the ‘Theory of Emergence’. I cannot give a conclusive example of it, since it is a matter of controversy whether it actually applies to anything ... I will merely remark that, so far as I know at present, the characteristic behaviour of Common Salt cannot be deduced from the most complete knowledge of the properties of Sodium in isolation; or of Chlorine in isolation; or of other compounds of Sodium, ..."

A Test for Emergence

1) **Design:** The system has been constructed by the designer, by describing local elementary interactions between components (e.g., artificial creatures and elements of the environment) in a language $L_1$.

2) **Observation:** The observer is fully aware of the design, but describes global behaviors and properties of the running system, over a period of time, using a language $L_2$.

3) **Surprise:** The language of design $L_1$ and the language of observation $L_2$ are distinct, and the causal link between the elementary interactions programmed in $L_1$ and the behaviors observed in $L_2$ is non-obvious to the observer - who therefore experiences surprise. In other words, there is a cognitive dissonance between the observer's mental image of the system's design stated in $L_1$ and his contemporaneous observation of the system's behavior stated in $L_2$.

Notice - It is often possible to get descriptions of emergent properties in terms of the elementary actions.

E.g., this is what Turing did for the role of Fibonacci numbers in relation to the sunflower etc.

In mathematics, it is well-known that complicated descriptions may take us beyond what is computable.

A potential source of surprise in emergence ...
Descriptions and Emergent Structure ...

- **Intuition** - entities exist because of, and according to, mathematical laws. In the words of Leibniz [1714] -

  - ‘The Monadology’, section 32:
    “... there can be found no fact that is true or existent, or any true proposition, without there being a sufficient reason for its being so and not otherwise, although we cannot know these reasons in most cases.”
Definability the key concept

- That is - natural phenomena not only *generate* descriptions, but *arise and derive form* from them...

... so - connecting with a useful abstraction - that of mathematical definability - or, more generally, invariance (under the automorphisms of the appropriate structure)...

- ... giving precision to our experience of emergence as a potentially non-algorithmic determinant of events
Symmetries play a huge role in science..

... expressing appropriate automorphisms

... or particular lapses in definability

... so giving a clear route: from fundamental mathematical structures, and their automorphisms and breakdowns in definability - to far-reaching macro-symmetries in nature
I believe the following aspects of evolution to be true, without knowing how to turn them into (respectable) research topics.

**Important steps in evolution are robust.** Multicellularity evolved at least ten times. There are several independent origins of eusociality. There were a number of lineages leading from primates to humans. If our ancestors had not evolved language, somebody else would have.

**Martin Nowak,**
Director, Program for Evolutionary Dynamics, Harvard University,
in John Brockman (ed.): “What We Believe But Cannot Prove”
Emergence and Mentality

“At first Poincaré attacked [a problem] vainly for a fortnight, attempting to prove there could not be any such function ... [quoting Poincaré]:

‘Having reached Coutances, we entered an omnibus to go some place or other. At the moment when I put my foot on the step, the idea came to me, without anything in my former thoughts seeming to have paved the way for it ... I did not verify the idea ... I went on with a conversation already commenced, but I felt a perfect certainty.

On my return to Caen, for conscience sake, I verified the result at my leisure.’

from Jacques Hadamard [1945], “The Psychology of Invention in the Mathematical Field”, Princeton Univ. Press
Supervenience ‘represents the idea that mentality is at bottom physically based, and that there is no free-floating mentality unanchored in the physical nature of objects and events in which it is manifested.’


“A set of properties A supervenes upon another set B just in case no two things can differ with respect to A-properties without also differing with respect to their B-properties.”

Stanford Encyclopedia of Philosophy
How can mentality have a causal role in a world that is fundamentally physical?

And what about ‘overdetermination’ - the problem of phenomena having both mental and physical causes?

... the problem of mental causation is solvable only if mentality is physically reducible; however, phenomenal consciousness resists physical reduction, putting its causal efficacy in peril.

-Jaegwon Kim: Physicalism, or Something Near Enough, Princeton, 2005
There is a reasonable chance that connectionist models will lead to the development of new somewhat-general-purpose self-programming, massively parallel analog computers, and a new theory of analog parallel computation: they may possibly even challenge the strong construal of Church's Thesis as the claim that the class of well-defined computations is exhausted by those of Turing machines.

These have come a long way since Turing’s [1948] discussion of ‘unorganised machines’, and McCulloch and Pitts [1943] early paper on neural nets.

But for Steven Pinker “… neural networks alone cannot do the job”.

And focusing on our elusive higher functionality, he points to a “kind of mental fecundity called recursion” …
We humans can take an entire proposition and give it a role in some larger proposition. Then we can take the larger proposition and embed it in a still-larger one. Not only did the baby eat the slug, but the father saw the baby eat the slug, and I wonder whether the father saw the baby eat the slug, the father knows that I wonder whether he saw the baby eat the slug, and I can guess that the father knows that I wonder whether he saw the baby eat the slug, and so on.

Steven Pinker,
"As the brain forms images of an object - such as a face, a melody, a toothache, the memory of an event - and as the images of the object affect the state of the organism, yet another level of brain structure creates a swift nonverbal account of the events that are taking place in the varied brain regions activated as a consequence of the object-organism interaction. The mapping of the object-related consequences occurs in first-order neural maps representing the proto-self and object; the account of the causal relationship between object and organism can only be captured in second-order neural maps. ... one might say that the swift, second-order nonverbal account narrates a story: that of the organism caught in the act of representing its own changing state as it goes about representing something else."

- Antonio Damasio [1999], The Feeling Of What Happens, p.170
Definability in What Structure?

- In modelling the physical universe -

... causality itself is fundamental

Early champions of the role of causality - Roger Penrose, Rafael Sorkin, Fay Dowker, and Fotini Markopoulou

It is not only the case that the spacetime geometry determines what the causal relations are. This can be turned around: Causal relations can determine the spacetime geometry ...

It’s easy to talk about space or spacetime emerging from something more fundamental, but those who have tried to develop the idea have found it difficult to realize in practice. ... We now believe they failed because they ignored the role that causality plays in spacetime. These days, many of us working on quantum gravity believe that causality itself is fundamental - and is thus meaningful even at a level where the notion of space has disappeared.

Lee Smolin, The Trouble With Physics, p.241
The Turing model extended ...

- 1939 - Turing’s oracle Turing machines

- Provide a model of computable content of structures, based on p.c. functionals over the reals

- A model within which Newtonian computability etc comfortably fit ...
The Turing model extended...

- 1939 - Turing’s oracle Turing machines
- Provide a model of computable content of structures, based on p.c. functionals over the reals
- 1944 - Post defines the degrees of unsolvability as a classification of reals in terms of their relative computability
- Giving a landscape with a rich structure
The Turing landscape, causality and emergence ...

- Can describe global relations in terms of local structure ...
- ... so capturing the emergence of large-scale formations

Mathematically - formalise as definability over structure based on Turing functionals?

More generally - as Invariance under automorphisms
Fundamental problem: Characterise the Turing invariant relations

- Intuition: These are key to pinning down how basic laws and entities emerge as mathematical constraints on causal structure

- Notice: The richness of Turing structure discovered so far becomes the raw material for a multitude of non-trivially definable relations
Notice: Conjecture rules out there being non-trivial Turing automorphisms ...

But: Work over the years makes it increasingly unlikely ...
An Informational Universe

Described in terms of reals ... With natural laws based on algorithmic relations between reals.

Emergence described in terms of definability/invariance.

... with failures of definable information content modelling mental phenomena, quantum ambiguity.

... which gives rise to new levels of computable structure.

... and a fragmented scientific enterprise.
Footnote: Downward Causation Revisited

The “levels” involved are levels of organisation and integration, and the downward influence means that the behavior of “lower” levels - that is, of the components of which the “higher-level” structure consists - is different than it would otherwise be, because of the influence of the new property that emerges in consequence of the higher-level organization.

Thank you!