Quick takes on some ideas and discoveries in *A New Kind of Science*

Mathematical equations do not capture many of nature's most essential mechanisms
For more than three centuries, mathematical equations and methods such as calculus have been taken as the foundation for the exact sciences. There have been many profound successes, but a great many important and obvious phenomena in nature remain unexplained—especially ones where more complex forms or behavior are observed. *A New Kind of Science* builds a framework that shows why equations have had limitations, and how by going beyond them many new and essential mechanisms in nature can be captured.

Thinking in terms of programs rather than equations opens up a new kind of science
Mathematical equations correspond to particular kinds of rules. Computer programs can embody far more general rules. *A New Kind of Science* describes a vast array of remarkable new discoveries made by thinking in terms of programs—and how these discoveries force a rethinking of the foundations of many existing areas of science.

Even extremely simple programs can produce behavior of immense complexity
Everyday experience tends to make one think that it is difficult to get complex behavior, and that to do so requires complicated underlying rules. A crucial discovery in *A New Kind of Science* is that among programs this is not true—and that even some of the very simplest possible programs can produce behavior that in a fundamental sense is as complex as anything in our universe. There have been hints of related phenomena for a very long time, but without the conceptual framework of *A New Kind of Science* they have been largely ignored or misunderstood. The discovery now that simple programs can produce immense complexity forces a major shift in scientific intuition.

Simple programs can yield behavior startlingly like what we see in nature
How nature seems so effortlessly to produce forms so much more complex than in typical human artifacts has long been a fundamental mystery—often discussed for example in theological contexts. *A New Kind of Science* gives extensive evidence that the secret is just that nature uses the mechanisms of simple programs, which have never been captured in traditional science.

Simple programs can do much more than typical programs written by programmers
A New Kind of Science shows that extremely simple programs picked for example at random can produce behavior that is far more complex than typical programs intentionally set up by programmers. The fundamental engineering concept that one must always be able to foresee the outcome of programs one writes has prevented all but a tiny fraction of all possible programs from being considered. The idea of allowing more general programs has great potential significance for technology.

Simple computer experiments reveal a vast world of new phenomena
In their times both telescopes and microscopes revealed vast worlds that had never been seen before. Through the ideas of *A New Kind of Science*, computer experiments now also reveal a vast new world, in many ways more diverse and surprising even than the world seen in astronomy, or than the flora and fauna discovered by explorers of the Earth in past centuries. Many of the basic experiments in *A New Kind of Science* could in principle have been done by mosaic makers thousands of years ago. But it took new intuition and new tools to unlock what was needed to do the right experiments and understand their significance.

Randomness in physics can be explained by mechanisms of simple programs
Despite attempts from approaches like chaos theory, no fundamental explanation has ever been found for randomness in physical phenomena such as fluid turbulence or patterns of fracture. *A New Kind of Science* presents an explanation based on simple programs that for example predicts surprising effects such as repeatable randomness.

Thermodynamic behavior can be explained by mechanisms of simple programs
The Second Law of Thermodynamics (Law of Entropy Increase) has been a foundational principle in physics for more than a century, but no satisfactory fundamental explanation for it has ever been given. Using ideas from studying simple programs, *A New Kind of Science* gives an explanation, and in doing so shows limitations of the Second Law.

Complexity in biology can be explained by mechanisms of simple programs
From traditional intuition one expects that the observed complexity of biological organisms must have a complex origin—presumably associated with a long process of adaptation and natural selection. *A New Kind of Science* shows how complex features of many biological organisms can be explained instead through the inevitable behavior of simple programs associated with their growth and development. This implies that biology need not just reflect historical accidents, and that a general study of simple programs can lead to a predictive theory of at least certain aspects of biology.

Simple programs may lay the groundwork for new insights about financial systems
The underlying mechanism that leads for example to seemingly random fluctuations in prices in markets has never been clear. Discoveries about simple programs—such as the phenomenon of intrinsic randomness generation—provide potentially important new insights on such issues.

Our whole universe may be governed by a single underlying simple program
In its recent history, physics has tried to use increasingly elaborate mathematical models to reproduce the universe. But building on the discovery that even simple programs can yield highly complex behavior, *A New Kind of Science* shows that with appropriate kinds of rules, simple programs can give rise to behavior that reproduces a remarkable range of known features of our universe—leading to the bold assertion that there could be a single short program that represents a truly fundamental model of the universe, and which if run for long enough would reproduce the behavior of our universe in every detail.

Underlying space there may be a simple discrete structure
Throughout almost the entire history of science, space has been viewed as something fundamental —and typically continuous. *A New Kind of Science* suggests that space as we perceive it is in fact not fundamental, but is instead merely the large-scale limit of an underlying discrete network of connections. Models constructed on this basis then lead to new ideas about such issues as the origins of gravity and general relativity, the true nature of elementary particles and the validity of quantum mechanics.

Time may have a fundamentally different nature from space
The standard mathematical formulation of relativity theory suggests that—despite our everyday impression—time should be viewed as a fourth dimension much like space. *A New Kind of Science* suggests however that time as we perceive it may instead emerge from an underlying process that makes it quite different from space. And through the concept of causal invariance the properties of time seem to lead almost inexorably to a whole collection of surprising results that agree with existing observations in physics—including the special and general theories of relativity, and perhaps also quantum mechanics.

Systems with exceptionally simple rules can be universal computers
Seeing the complicated circuitry of existing computers, one would think that it must take a complicated system to be able to do arbitrary computation. But *A New Kind of Science* shows that this is not the case, and that in fact universal computation can be achieved even in systems with very simple underlying rules. As a specific example, it gives a proof that the so-called rule 110 cellular automaton—whose rules are almost trivial to describe—is universal, so that in principle it can be programmed to perform any computation. And as a side result, this leads to by far the simplest known universal Turing machine.

Many systems in nature are capable of universal computation
If universal computation required having a system as elaborate as a present-day computer, it would be inconceivable that typical systems in nature would show it. But the surprising discovery that even systems with very simple rules can exhibit universality implies that it should be common among systems in nature—leading to many important conclusions about a host of fundamental issues in science, mathematics and technology.

The Principle of Computational Equivalence provides a broad synthesis
Many of the discoveries in *A New Kind of Science* can be summarized in the bold new Principle of Computational Equivalence, which states in essence that processes that do not look simple almost always correspond to computations of exactly equivalent sophistication. This runs counter to the implicit assumption that different systems should do all sorts of different levels and types of computations. But the Principle of Computational Equivalence has the remarkable implication that instead they are almost all equivalent—leading to an almost unprecedentedly broad unification of statements about different kinds of systems in nature and elsewhere.

Many systems in nature are computationally equivalent to us as humans
We would normally assume that we as humans are capable of much more sophisticated computations than systems in nature such as turbulent fluids or collections of gravitating masses. But the discoveries in *A New Kind of Science* imply that this is not the case, yielding a radically new perspective on our place in the universe.

Many systems in nature can show features like intelligence
Statements like "the weather has a mind of its own" have usually been considered not scientifically relevant. But the Principle of Computational Equivalence in *A New Kind of Science* shows that processes like the flow of air in the atmosphere are computationally equivalent to minds, providing a major new scientific perspective, and reopening many debates about views of nature with an animistic character.

Extraterrestrial intelligence is inevitably difficult to define and recognize
It has usually been assumed that detecting extraterrestrial signals from a sophisticated mathematical computation would provide evidence for extraterrestrial intelligence. But the discoveries in *A New Kind of Science* show that such computation can actually be produced by very simple underlying rules—of kinds that can occur in simple physical systems with nothing like what we normally consider intelligence. The result is a new view of the character of intelligence, and a collection of ideas about the nature of purpose, and recognizing it in ultimate extrapolations of technology.

It is easy to make randomness that we cannot decode
One might have thought that we would always be able to recognize signs of the simplicity of an underlying program in any output it produces. But *A New Kind of Science* studies all the various common methods of perception and analysis that we use, and shows that all of them are ultimately limited to recognizing only specific forms of regularity, which may not be present in the behavior of even very simple programs—with implications for cryptography and for the foundations of fields such as statistics.

Apparent complexity in nature follows from computational equivalence
We tend to consider behavior complex when we cannot readily reduce it to a simple summary. If all processes are viewed as computations, then doing such reduction in effect requires us as observers to be capable of computations that are more sophisticated than the ones going on in the systems we are observing. But the Principle of Computational Equivalence implies that usually the computations will be of exactly the same sophistication—providing a fundamental explanation of why the behavior we observe must seem to us complex.

Many important phenomena are computationally irreducible
Most of the great successes of traditional exact science have ultimately come from finding mathematical formulas to describe the outcome of the evolution of a system. But this requires that the evolution be computationally reducible, so that the computational work involved can just be reduced to evaluation of a formula. *A New Kind of Science* shows however that among most systems computational reducibility is rare, and computational irreducibility is the norm. This explains some of the observed limitations of existing science, and shows that there are cases where theoretical prediction is effectively not possible, and that observation or experiment must inevitably be used.

Apparent free will can arise from computational irreducibility
For centuries there has been debate about how apparent human free will can be consistent with deterministic underlying laws in the universe. The phenomenon of computational irreducibility described in *A New Kind of Science* finally provides a scientifically based resolution of this apparent dichotomy.

Undecidability occurs in natural science, not just mathematics
The phenomenon of formal undecidability discovered in mathematics in the 1930s through Gödel's Theorem has normally been viewed as esoteric, and of little relevance to ordinary science. *A New Kind of Science* shows however that undecidability is not only possible but actually common in many systems in nature, leading to important philosophical conclusions about what can and cannot be known in natural science.

The difficulty of doing mathematics reflects computational irreducibility
Mathematical theorems such as Fermat's Last Theorem that are easy to state often seem to require immensely long proofs. In *A New Kind of Science* this fundamental observation about mathematics is explained on the basis of the phenomenon of computational irreducibility, and is shown to be a reflection of results like Gödel's Theorem being far more significant and widespread than has been believed before.

Existing mathematics covers only a tiny fraction of all possibilities
Mathematics is often assumed to be very general, in effect covering any possible abstract system. But the discoveries in *A New Kind of Science* show that mathematics as it has traditionally been practiced has actually stayed very close to its historical roots in antiquity, and has failed to cover a vast range of possible abstract systems—many of which are much richer in behavior than the systems actually studied in existing mathematics. Among new results are unprecedentedly short representations of existing formal systems such as logic, used to show just how arbitrarily systems like these have in effect been picked by the history of mathematics. The framework created in *A New Kind of Science* provides a major generalization of mathematics, and shows how fundamentally limited the traditional theorem-proof approach to mathematics must ultimately be.

Studying simple programs can form a basis for technical education
As a vehicle for teaching precise analytical thinking, *A New Kind of Science* represents a major alternative to existing mathematics, with such advantages as greater explicitness and visual appeal, more straightforward applicability to certain issues in natural science, and side benefits of learning practical computer science and programming.

Mechanisms from simple programs suggest new kinds of technology
In existing technology complex tasks tend to be achieved by systems with elaborately arranged parts. But the discoveries in *A New Kind of Science* show that complex behavior can be achieved by systems with an extremely simple underlying structure—that is for example potentially easy to implement at an atomic scale. Many specific systems, such as cellular automata, studied in *A New Kind of Science* are likely to find their way into a new generation of technological systems.