Chaos, complexity and complicatedness: lessons from rocket science

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CONTEXT Recently several authors have drawn parallels between educational research and some theories of natural science, in particular complexity theory and chaos theory. The central claim is that both the natural science theories are useful metaphors for education research in that they deal with phenomena that involve many variables interacting in complex, non-linear and unstable ways, and leading to effects that are neither reproducible nor comprehensible.

METHODS This paper presents a counter-argument. I begin by carefully examining the concepts of uncertainty, complexity and chaos, as described in physical science. I distinguish carefully between systems that are, respectively, complex, chaotic and complicated. I demonstrate that complex and chaotic systems have highly specific characteristics that are unlikely to be present in education systems. I then suggest that, in fact, there is ample evidence that human learning can be understood adequately with conventional linear models.

CONCLUSIONS The implications of these opposing world views are substantial. If education science has the properties of complex or chaotic systems, we should abandon any attempt at control or understanding. However, as I point out, to do so would ignore a number of recent developments in our understanding of learning that hold promise to yield substantial improvements in effectiveness and efficiency of learning.
‘Chaos is a name for any order that produces confusion in our minds.’

George Santayana

INTRODUCTION

Your daughter, a university undergraduate, has a summer job with the city traffic department. She is looking at traffic speeds on the local freeway through town. Her team sets up a photographic radar device beside the road and measures the speed of cars passing by. Your daughter tells you that they discover that most of the time car speeds follow a normal distribution, with a mean of about 110 km/hour. Twice a day, at around 8.00 am and 5.00 pm, the average speed drops, and speeds, although still normally distributed, have a mean of only about 10 km/hour. But between 7.00 am and 8.00 am, and between 3.00 pm and 5.00 pm, speeds are completely erratic. Sometimes traffic moves smoothly at high speed past the point; sometimes it comes to a complete standstill and then, a few minutes later, speeds up again. When your daughter tells you this, you reflect a while and then say, ‘You know, that’s a really good metaphor for education!’

This brief scenario actually describes one everyday example of chaos theory, in which a relatively simple system, which behaves regularly most of the time, can, under some circumstances, revert to completely erratic and unpredictable motion. In this case, when vehicle density is low or very high, traffic flow is predictable. But when density is at a critical point, traffic flow can be disrupted by very small perturbations that may arise at locations far removed from the point of observation. The normal traffic flow is also a good example of a complex adaptive system. Individual units (vehicles and drivers) are highly heterogeneous, literally as diverse as the population, and there are no physical laws connecting these units and no communication between them. The motion of any individual unit (changing lanes, entering, leaving) is completely unpredictable, and the interactions between units are unknown and dynamic. Despite this, the flow of traffic exemplifies self-organisation, the hallmark of complexity, as all traffic flows in a single direction and changes direction together. Finally, the freeway is also a good example of a classic, Cartesian, deterministic, reductionist system, as it is trivial to show that a small intervention, such as changing a message on a white metal plate beside the road from ‘Maximum 100 km/hour’ to ‘Maximum 60 km/hour’, can result, in large, significant and replicable changes in outcome.

There are also two larger messages to be extracted from this example. Firstly, the scientific methods of identifying chaos or complexity in this situation are straightforward. You sit by the road and measure the speed of the cars going by. A graph of the standard deviation of traffic speed related to traffic density would illustrate both complexity and chaos. No new methodologies are required. Secondly, the last line in the story is a deliberate non sequitur; it seems highly unlikely that anyone would gain insight into the process of learning and teaching from watching cars go by on the freeway and identifying complexity and chaos. Yet the idea that complexity theory and chaos theory may offer useful metaphors which may help us to understand the complexities of learning and teaching has become a recurrent theme in medical education, explored in detail in three recent papers.

Mennin1 argues that:

‘...existing paradigms in medical education ... have become fragmented and remain rooted in Cartesian reductionism and Newtonian principles of linear causality.’

He then describes complexity science as a better metaphor for the process of learning:

‘...a system that is open and far from equilibrium, with ill-defined boundaries and a large number of non-linear interactions involving short-loop feedback... It is complex because the whole cannot be understood by reducing it to its component parts, nor can it be described by simple linear equations... It is a system that is open to the outside world and is continuously exchanging energy with its surroundings. It is affected by, and in turn, affects its environment.’

Critical to this viewpoint, then, is the notion of non-linear, interacting, unbounded systems. Following Radford,2 Mennin distinguishes between ‘complicated’ systems that ‘tend to be understood in terms of measurable variables that remain relatively stable’ and ‘complex’ systems in which ‘the influence of any particular factors is variable according to the relationships that they enjoy with others at any moment of time ... within the context of interaction between the elements new variables or characteristics may emerge that cannot be accounted for within the context of the interacting components but only in that of the interacting process itself’.1

Regehr3 also begins by describing a crisis in medical education, in which ‘something is amiss with the
practice of research in the medical education field’. Like Mennin,1 he points to problems created by the ‘hypothesis-testing framework’, drawn from the physical sciences, that has been ‘adopted and adapted into an implicit “imperative of proof”’.2 He then draws metaphors from modern subatomic physics and from chaos theory to illustrate the fundamental idea that physical science has moved on from its quest for simplicity to a ‘construct of uncertainty’. He similarly draws upon a discussion of complexity, suggesting that when everything interacts, nothing is simple, and that ‘the effect of a single variable is not merely hidden in the noise of other variables. Rather its effect is fundamentally transformed through those other variables’.3 Regehr spends most of his discourse, however, describing chaos theory, and how the idea of chaotic systems that lack predictability may well be a useful metaphor for education research.3

Durning et al.4 take a similar approach by investigating the role of context in understanding the clinical encounter. Although they explore a number of metaphors, they, like Regehr2 and Mennin,1 are attracted to ‘theories that emphasise non-linearity, or the idea that the sum may be more than the individual parts’.4 They begin with chaos theory, a ‘prototypical non-linear mathematical model’, then go on to quantum mechanics and the Heisenberg Uncertainty Principle.

Common to these metaphors are two underlying and related concepts: non-linearity and uncertainty. Both chaos theory and complexity theory describe how non-linear relationships can combine in such a way that, under some circumstances, the ultimate state of the system is unpredictable. However, they are correct, then we really need to rebuild our research enterprise from the ground up, leaving the entire reductionist approach and conventional statistics behind.

Certainly, some of their assertions seem to ring true. When we reflect on education systems or other complex organisations, it does seem that our attempts to arrive at anything resembling generalisable truths are often quixotic. Systematic reviews of, say, the effectiveness of high-fidelity simulations5 result in such diversity of treatments and effects that the variability in results under different conditions becomes more interesting than the overall effect. Similarly, of 10 published Best Evidence Medical Education (BEME) systematic reviews, only one6 was able to compute overall effect sizes. The remainder devolved to critical reviews, counting how many papers did what, what each found, and so on.

Is this real evidence that the positivist reductionist paradigm is wrong and needs to be abandoned? Are things in education really too complex and chaotic to yield to meaningful description or experimental manipulation? Should we abandon any attempt to look for universals? Before we adopt these alternative precepts as new guiding principles, it is imperative that we ‘get it right’ and assure our community that they are valid metaphors, for the simple reason that the implications of this ‘new science’ of education would be immense. Experimentalists would go out of business, but, more to the point, a wholesale abandonment of the positivist approach and the accompanying deliberate search for universals would run the real risk of ignoring a substantial body of literature based on these approaches that demonstrate the effectiveness of many theory-based educational interventions.

In this paper, I wish to explore in detail the metaphors used by these writers in making their claims. I distinguish between complicated, complex and chaotic systems. I carefully explore the underlying assumptions of each system to identify if it is applicable to the world of education. Finally, I look critically at education and psychology research to determine whether, in fact, there is any evidence to justify the claim that our field is either chaotic or complex in the technical sense.

As a starting point, I will conduct a careful examination of the characteristics of these descriptions in their original form, as a step toward understanding if they are indeed valid descriptions of the ‘state of the world’ in education. In these definitions, I follow the descriptions of Mennin, Radford and Regehr.1–3 The formal characteristics of these systems are as follows:

- A system is complicated if it contains many variables which combine in linear and predictable ways so their effects can be isolated and their overall impact on the system is ultimately knowable. This is a description of the present paradigm, in which the assumption is that relationships among variables can be captured adequately with systems of linear equations.
- A system is chaotic if it is governed by non-linear relationships which combine in such a way that, under some circumstances, the ultimate state of the system is unpredictable. However, the variables themselves are explicit and knowable and may be few in number. Moreover, the system may be completely deterministic in some choices of parameters, but chaotic in other regions.
• A system is complex if, in addition to non-linear relationships, it is characterised by multiple indefinable variables interacting in indefinable, unstable and ultimately unknowable ways so that no system of linear equations can represent the reality. In addition, a complex adaptive system also exhibits large-scale regularities (self-organisation) that cannot be extrapolated from the properties of individual elements.

In some respects, complex and chaotic systems are opposites. Although both result from non-linear and interacting relationships, a complex system may contain many variables interacting in complex and indefinable ways, but the outcome may be regular and predictable, whereas a chaotic system may have very few variables with apparently simple relationships, but, under some circumstances, its outcome becomes completely unpredictable. Complicated systems, however, are consistent with a classical deterministic view of the world.

The fundamental distinction I wish to make is that between chaotic and complex systems, in which there are no deterministic, stable, linear relationships among the variables, and complicated systems, in which the relationships among the often many variables are stable and result in replicable outcomes.

UNDERSTANDING THE PHYSICS

Both Regehr and Durning et al. draw parallels between the present epistemological crisis in education science and trends in modern physics. Regehr traces the history of physics from Newton’s Laws to the complexity of modern subatomic physics. He states: ‘Through the discovery of these [quantum uncertainty and entanglement] and other phenomena, the basic imperative of physics shifted from the construct of simplicity to a construct of uncertainty.’

Although certain (but not all) quantum mechanical phenomena contain an irreducible uncertainty, expressed in the Heisenberg Uncertainty Principle, this is not a general characteristic of all modern physics. \( E = mc^2 \) is a deceptively simple equation derived from the theory of special relativity, which is very difficult to understand, even though it is completely deterministic. Its successor, general relativity, is notoriously complicated, but it is solvable, and hence not complex (in the technical sense of being insoluble in principle).

As one example, the critical test of general relativity occurred in 1920, when it was able to account for 43 seconds of arc per century in the advance of the perihelion of Mercury’s orbit, which Newton’s Laws could not explain. The precision of both the measurements and the predictions is impressive: the missing ‘error’ amounts to 0.00003 degrees of constant error in the calculated advance per revolution of Mercury around the sun. So general relativity is complicated, but it is not chaotic and it is not complex, in the technical sense described above.

In any case, although quantum physics is inherently probabilistic, this does not preclude precise prediction about quantum phenomena. Although we may not be able to predict when a particular atom of Tc will decay, we can say with absolute confidence that all atoms will decay by emitting a gamma ray of 140 keV and that half will have done so every 6.00 hours. The fact that the theory’s predictions are probabilistic is neither consequential nor so divorced from everyday experience. We cannot predict exactly when in the fall a particular leaf will drop from a tree, but we can say with some confidence that all will have fallen by December 1 (at least in my part of the world). We cannot say with any certainty when a woman with stage IV breast cancer will succumb to her illness, but we can say with near certainty that her chance and duration of survival will be less than those of a woman with stage I cancer. Yes, it is true that quantum mechanical leaves are both on the tree and on the ground until observed, but this, like Heisenberg Uncertainty, applies only in the submicroscopic world of the quantum. It does not mean we do not or cannot understand biosynthesis, nuclear decay or breast cancer. Many physical and biological phenomena are very complicated, but this does not imply that they defy understanding.

Chaos theory

Although it is appealing to envision that chaos somehow affords an explanation for the complexities we observe in the world around us (particularly if we use it as a metaphor by which to explain occurrences in education), chaos as a physical theory has some very specific conditions. For a system to be chaotic, the solution must be indeterminate. An essential requirement is that the equations of motion, relating force to velocity and acceleration, are non-linear. But chaotic systems can, paradoxically, be very simple. Blackburn et al. constructed a very simple mechanical pendulum, the standard ‘weight on a string’, with one small addition: an electromagnet that adds some rotating motion to the swing. Blackburn describes it:
Some choices (of frequencies) result in complex but repetitive motion, as one might expect from the fact that this system contains only two basic frequencies – the natural frequency of the pendulum itself, and the (different) forcing frequency. However, many other choices lead to chaotic motion where the mix of oscillatory and rotating motion NEVER repeats itself – the hallmark of chaos... But here is the KEY point about chaos: this noise is not a reflection of random processes. The system contains no source of randomness. It is just an ideal inherently non-linear oscillator plus an ideal harmonic drive term. So out of these very well-behaved ingredients one finds unpredictability and noise! What would Newton have said? He would say ‘determinism’ – you give me the complete initial conditions and I will predict the motion forever in the future. But that is not the case for this system.’ (J A Blackburn, personal communication, 2010)

It is hard to imagine a simpler system. Undergraduate physics students learn the law of motion of a pendulum very early – the simple equation is easily derived from classical Newtonian mechanics. All Blackburn did was ‘twist the string’ at a different frequency and that induced complex and unpredictable ‘chaotic’ motion.

Chaos can apply to many phenomena: water from a tap; smoke from a cigarette, traffic flow. But the systems are simple. Thus, although it is tempting to seize on chaos as a perfect metaphor for education in that the system is inherently unpredictable, the very simplicity of some chaotic systems and the fact that the motion is perfectly predictable with some choices of starting parameters, but completely unpredictable with others, make it a poor analogy. It is one thing to say that chaos is a good metaphor for education; it is quite another to say that a pendulum is. Blackburn (personal communication, 2010) elegantly conclude:

‘People confuse chaos, as we define it, and disorder. Chaos is a very particular phenomenon that arises in many non-linear systems, it is not behind every data set that appears to be hopelessly scrambled.’

Complexity theory

Paradoxically, complexity theory is in some ways the exact opposite of chaos theory. Although both reflect properties of non-linear systems, complexity theory shows how regularities – ‘self-organisation’ – can arise from multiple interactive, non-linear and changing elements. Put simply: ‘Complexity Theory looks at how complex systems can generate simple outcomes.’

Chaos, complexity and complicatedness

The dilemma that pertains to applying complexity theory to education is that, in one sense, it is a solution to the wrong problem. Our challenge in education is not to explain overall regularities while ignoring individual interactions. Despite the anecdotes used by Mennin and Regehr,1,3 well-grounded educational interventions can lead to large and reproducible effects on learning. Further, we actually understand quite a bit about the variables and interactions that lead to learning at the individual level, perhaps more than is required for modelling by complexity theory. Hence, modelling overall effects is something we do quite well. Even though we cannot predict exactly how much an individual student or, by extension, perhaps an individual classroom, may learn, we can state with confidence that some learning conditions are superior to others. I will return to this point later.

LESSONS FROM ROCKET SCIENCE

Apparent complex situations may hide simple relationships.

Regehr’s title5 states that education is not rocket science, principally because, as he describes, rocket science is ‘built on a structured linear system with a straightforward set of factors which we can stick into a well-articulated formula to predict a clearly articulated outcome’. Rocket science is deterministic; education science is not. In the present framework, rocket science is complicated; education science (according to Regehr5, Mennin1 and Durning, et al.4) is complex and/or chaotic.
Certainly, the ability of NASA to position satellites and space shuttles into precise orbits far from Earth is a good example of a system that is both complicated and deterministic. The calculation of the trajectory of a spacecraft wending its way from Earth to Pluto requires extensive computations that take into consideration the combined gravitational forces of all the planets and moons simultaneously. But it is based on Newton’s Laws, which were developed 400 years ago.

However, not everything about space science is deterministic and certain, as the two disasters in the space programme attest. In his commentary on Regehr’s paper,3 Eva11 mentions the Challenger disaster of 1986, when the space shuttle Challenger exploded 73 seconds after launch as a result of the blowby of hot gases through a rubber O-ring on a booster rocket. The disaster led to a congressional inquiry and was analysed in dozens of scientific papers.

The history of the disaster has been reviewed by Tufte.12 In brief, engineers at NASA and Morton Thiokol, the maker of the boosters, had known of a possible association between ambient temperature at launch and the probability of blowby for some time, as a result of analysis of prior launches. The launch date was forecast to have unusually low temperature and so discussions went back and forth long into the night before launch. As Tufte indicates, the discussions were heated and many opinions were voiced.12 In many respects, an observer might well have concluded that this was almost exactly the kind of complex, non-linear, unpredictable interpersonal situation that Mennin1 describes with reference to educational institutions.

An example (Fig. 1) of the tables faxed back and forth reveals, buried in many other statistics, a concern in relation to temperature.

However, rather than being an example of complexity leading to indeterminate outcomes, the disaster had a single cause which could have been acted upon and the accident averted. If the engineers had only drawn a graph showing the degree of blowby against temperature, as Tufte12 did (Fig. 2), leaving out the many other variables like wind direction, speed, location of blowby, etc., they would have seen a strong inverse relation to temperature, which made blowby at the launch temperature, and the deaths of the astronauts that fateful day, a virtual certainty.

The complex culture of the space programme was undoubtedly a factor in the sequence of events that led to the Challenger disaster, evidenced by the fact that its engineers had long and sometimes heated discussions, but ultimately made the wrong decision. However, a good graph, vividly showing a simple cause–effect relationship, might have averted the catastrophe. Thus, although the situation had all the appearances of complexity, in fact, the relationship between temperature and blowby was straightforward and deterministic.

There is an obvious parallel. Although educational environments are complex and multi-dimensional, involving many players with many competing and changing interests, this does not preclude the possibility that simple interventions based on sound evidence can have large beneficial effects on learning. Just as Mennin1 exhorts us to study the complexity of schools and curricula, no doubt psychologists and sociologists have studied the interactions among the

Figure 1 Example of a memo faxed between engineers at Morton Thiokol and NASA before the Challenger launch. Tufte, E. Visual Explanations: Images and Quantities, Evidence and Narrative.12 Reproduced by permission
NASA and Morton Thiokol engineers and the organisations within which they functioned to try to determine what kind of collective cognitive bias caused them to miss what was, in hindsight, an obvious relationship. However, although such studies in both education and rocket science may be worthwhile in their own right, we should not lose sight of the fact that, to prevent another such incident, you either design better O-rings or launch at higher temperatures. Similarly, the fact that medical schools are complicated places does not ameliorate the impact that specific instructional interventions may have on learning.

THE COUNTER-ARGUMENT: IS LEARNING REALLY SO COMPLEX AND CHAOTIC?

Do we have any evidence that education contains the elements necessary to justify its inclusion as either a complex or a chaotic system? Let me now explore some examples from education and psychology to assert that, although many variables may influence learning, it may not be particularly complex or chaotically indeterminate.

As one example, human judgement may appear to be among the most complex of cognitive activities, far more so than the rote learning that was the subject of many early investigations in psychology. Surprisingly, evidence from a number of lines of inquiry suggests otherwise. Firstly, studies in the ‘policy-capturing’ tradition, dating back to classic work in the 1960s by Hoffman,13 Meehl14 and others showed that human judgements in complex tasks involving the synthesis of multiple cues could be predicted quite well by a linear regression equation; in fact, an equal-weight equation frequently yielded the best prediction.15

As another example, systematic research into the nature of clinical reasoning suggests that, in routine cases, clinical reasoning proceeds by pattern-matching on the basis of similarity.16 Large effects of similarity can be observed in experiments with both experts and novices.17,18 Although the psychological processes of pattern recognition are fascinating, no appeal to complex or non-linear and unstable systems is required for explanation.

There is, in fact, evidence that education research, as a whole, is well characterised by linear main effects, not complex interactions. In an insightful paper written in 1957, Cronbach19 identified two distinct streams in psychology: the correlational and the experimental. The former was concerned with individual differences such as in personality, learning style and aptitudes; the latter referred to educational or psychological interventions. Cronbach19 advocated a strategy to reconcile the two positions by conscious effort to study ‘aptitude–treatment interactions’ (ATIs) or to establish what intervention is best for what kind of student. In doing so, he set off on a 15-year search for ATIs, a search that was overwhelmingly unsuccessful and which he abandoned in a follow-up paper published in 1975.20 Sadly, we still seek ATIs when we embark on studies of, for example, learning style and its relation to instruction,21 and, not surprisingly, these searches have been similarly fruitless.

Of course, one response is that two-way interactions are too simplistic and the world of learning is too complex to yield to such mechanical solutions. To paraphrase Cronbach, the ‘complexity theorist’ is ‘in love with just those complex interactions that the experimentalist abhors’.19,20 But if one is to sustain a claim that the real interest lies in the residual error term after all the simple effects have been accounted for, sooner or later the onus is on the claimant to show that there is meaningful knowledge to be gained by unpacking the residual. If you want to claim that the unexplained variance is evidence of ‘something else’, it is up to you to figure out what that
something else is. To date, exhortations to treat the world of education as complex or chaotic have been bereft of any strategy to explore such complexity.

By contrast, there is substantial evidence that interventions based on cognitive theories can lead to large and predictable effects on learning. The basis for these interventions is a well-grounded theory, which is a prerequisite for insight. Without theory as a lens through which to view the world, it might well appear to be a very complicated place. As an example, cognitive load theory\(^2\) has proved to be a very powerful basis for examining educational technologies. It derives from simple and well-understood aspects of human memory, particularly the limitations of short-term memory. Studies derived from cognitive load theory that look at aspects of presentation of learning materials\(^22,23\) consistently show large and replicable effects on learning. Some other strong manipulations involve distributed practice, in which learning is spread out over time and re-learning occurs,\(^24\) and mixed practice, in which examples of different solutions are mixed up.\(^25\) Periodic testing has been shown to consistently show effects on learning larger than those of equivalent self-study time.\(^26\) All of these are examples showing that simple educational interventions can lead to large and reproducible effects on learning. And all can be easily incorporated in medical curricula.\(^27\)

Although these interventions may not match the precision we saw in the prediction of Mercury's orbit, in fact, education is in better shape than medicine in that many effective medical therapies have much smaller effect sizes.\(^28,29\) Yet no-one is suggesting we abandon medical research because the human body is just too darn complex to ever be understood.

**WILL IT WORK IN THE REAL WORLD?**

Central to the arguments of both Regehr\(^3\) and Mennin\(^1\) is the claim that these effects can only be observed because they were conducted in tightly controlled laboratory settings and that they would not replicate ‘in the real world’. Regehr goes further, describing a process in which repeated failures are ignored and only occasional successes proceed to publication.\(^3\)

There are many differences between the lab and the real world, but just because the studies have taken place in a lab does not necessarily imply that their findings will not generalise. It is not that the relationships are different; it’s just that there are more of them and so the effect of any one variable may not be as visible. In any case, the boundary between the learning lab and the real world is not well demarcated. Many of the studies that exemplify some of the theories described above incorporated an experimental manipulation into a ‘real world’ instructional programme. Here are some examples:

1. Hatala et al.\(^{25}\) taught medical students to read electrocardiographs (ECGs) from three different diagnostic categories. All students saw the same instruction and the same practice examples. However, in one group, 12 practice examples were mixed together (mixed practice); in the other all examples from a category were shown together (blocked practice). Total instructional time was controlled. On new materials, the mixed group had an accuracy of 46% and the blocked group 30% (effect size [ES] = 1.6).

2. Raman et al.\(^{24}\) taught nutrition concepts in the course of an academic half-day to residents at Calgary and Toronto. In one group (distributed), concepts were taught for 1 hour each week over 4 weeks; in the other, concepts were taught for a single 4-hour session (blocked). Three months later, the distributed group showed a gain of 18% over baseline, whereas the massed group gained only a third (6%) as much (ES = 1.46).

3. Larsen et al.\(^{30}\) gave residents a teaching session on two topics: status epilepticus and myasthenia gravis. Residents were randomised to two counter-balanced groups. One group took tests on status epilepticus and studied a review sheet on myasthenia gravis, and the other took tests on myasthenia gravis and studied a review sheet on status epilepticus. Testing and studying occurred immediately after teaching and then twice more at intervals of about 2 weeks. Six months later, both groups were given a follow-up test. Residents who had taken tests after instruction had scores that were 50% higher (39% versus 26%) (ES = 0.68).

All of these studies represent controlled experiments. But all took place with realistic materials, in realistic settings, with real learners, as part of real curricula, and over timescales that are ‘real world’, and all showed large to very large effects. Studies such as these substantiate Norman’s claim that ‘advances in education are more likely to come from many small, tightly controlled studies, occurring in many labs, with many replications and with systematic variation of the factors in the interventions, driven by theories of the process’.\(^31\) The real danger in advocating an abandonment of reductionist education science is
that interventions such as these, derived from credible cognitive theories, will be ignored, to the potential loss of both researchers and, more importantly, learners.

LARGER LESSONS FROM NATURAL SCIENCE

Natural science has made remarkable achievements in the past 150 years. We understand the origin of the Universe 15 billion years ago and its evolution until now; we understand how galaxies and stars condensed out of a matter ‘soup’, how planets were formed, what conditions were necessary to form land, seas and atmospheres, how life emerged, and how higher life forms evolved. The advances in cosmology, physics, geology and molecular biology have been breathtaking. The extent of these discoveries, and their impact on our understanding of the world, are evidence of the power of the rationalist, reductionist, positivist, scientific method.

Nevertheless, it remains the case that, however large the effects we observe in our education experiments, we remain far from understanding or predicting individual actions. We can repeatedly demonstrate that mixed practice is superior to blocked practice, but some subjects in the blocked group will, some of the time, outperform some subjects in the mixed group. We may presume that this is because we do not know the individual’s full background; we do not have a full record of all meaningful ‘inputs’ for an individual human. However, such a notion rapidly moves from physics to metaphysics and considerations of consciousness, free will, and so forth.

But the issue at hand is whether this lack of predictability at the individual level represents an ultimate failure of classical scientific methods, or simply a psychosocial ‘uncertainty principle’ reflecting an ultimate limit on knowability (the irony of returning to this metaphor has not escaped me). Mennin31 and Regehr31 in their embrace of chaos theory, complexity theory and quantum uncertainty, presume that the problem is the former and that chaos and complexity theory offer an escape from this indeterminacy:

‘Research in medical education often seeks unsuccessfully to reduce complex systems to their component parts, searching for regular and predictable patterns of interaction… We will need to find new ways to study systems in which multiple variables are interacting simultaneously.’ Mennin

‘From a practical perspective, this complexity probably indicates that meaningful, simple, generalisable findings that address common problems in education are fundamentally unachievable.’ Regehr3

In arriving at these conclusions, both authors have inferred that the complexity of the phenomena will be better served by these new approaches. But every observation in this paper, from traffic flow, through Bénard cells, Blackburn’s pendulum and quantum uncertainty to mixed practice, was observed using classical reductionist methods. Both complexity and chaos are descriptions of phenomena, not prescriptions of methods. Although these authors1,3 (and others) claim that our methods must change to accommodate the new reality of complexity, uncertainty and chaos, in the physical world where they originated, these phenomena were investigated with classical, reductionist, experimental methods. Nowhere is this more obvious than in Blackburn’s pendulum,8 in which the simple act of changing the frequency of an oscillator induces chaotic behaviour. The motion of the pendulum outside the chaotic boundaries was completely predictable using a simple equation and the transition to chaotic motion was described using a simple plot of amplitude against frequency.

We have as yet no evidence that classical statistical methods, which begin with the assumption of independence of errors, and linear or, occasionally, simple non-linear relationships, are insufficient to model behavioural phenomena. Indeed, Mennin1 advocates the use of structural equation modelling (SEM) for investigating his new paradigm, although SEM retains the assumption of linear relations and independence of errors. Moreover, if classical methods were to fail, we would find little solace in the analytical methods of chaos and complexity theory. Not only are they mathematically complex, but they are very incomplete at this stage. In the physical world, it is relatively easy to experimentally create systems which will become chaotic under some choice of parameters, but paradoxically no theory can predict what values of the parameters will result in chaotic motion and none can model the motion that occurs. By contrast, it is possible, but not easy, to model the macroscopic changes of a complex system, but this reveals nothing about the individual elements (in our case, students) that comprise the whole system. It seems unlikely that application of these methods will lead to greater understanding.

Conversely, although the theories of chaos and complexity are complex, non-linear, interactive and
indeterminate; the experimental methods are reductionist. As McKerrow and McKerrow\textsuperscript{7} state with respect to the invocation of the Heisenberg Uncertainty Principle to support naturalistic research methods:

‘The principle was discovered in the context of the rationalist paradigm. This fact would appear to support the rationalist paradigm, not call into question its adequacy… It is incorrect to use the principle, which was discovered in the context of the rationalist paradigm, to negate the same paradigm and then use it to support arguments in favour of the naturalist paradigm.’\textsuperscript{7}

In the end, Mennin,\textsuperscript{1} Regehr\textsuperscript{3} and Durning \textit{et al.}\textsuperscript{4} present us with a paradox. On one hand, we are asked to reject the findings of reductionist, positivist education science, derived from the learning laboratory, as being too artificial to have any bearing on the ‘real world’ of education practice. In the next breath, we are asked to accept the findings of physics, using similar reductionist methods, to describe phenomena that are about as far removed from the world of education as imaginable. Richard Feynmann\textsuperscript{32} said, with reference to quantum mechanics:

‘Because atomic behaviour is so unlike ordinary experience, it is very difficult to get used to and appears peculiar and mysterious to everyone… it is perfectly reasonable that they should not [understand it] because all of direct human experience and of human intuition applies to large objects.’\textsuperscript{32}

Why theories from physical science would now be seen to provide a better metaphor for education than theories from psychology remains a mystery.

**CONCLUSIONS**

Judging by the number of commentaries about the nature and value of various kinds of education research that have appeared in the past few years, it seems that our field is at the cusp of a new era. In one respect, it seems there is growing dissatisfaction with our usual approaches to research and increasing acknowledgement of the apparent limitations of reductionist methods. In another, quantitative research based on the application of sound cognitive theories, such as cognitive load theory and dual processing theory,\textsuperscript{35} to real learning settings is showing large gains in effectiveness of learning, transfer and reasoning. Although there are few examples of implementation as yet, those there demonstrate a comfortable partnering with new technologies such as simulation and e-learning, which is now passing from ‘gee whiz’ status to being rationally incorporated in curricula.

The evidence from this research suggests that we should not despair of the complexities we encounter in the education setting. The world of learning is a complicated place; so is the atomic nucleus. Both contain a degree of randomness and unpredictability, the former far more than the latter. But both may also contain remarkable regularities. We can continue to accrue evidence (in the broadest sense) to help us elaborate the laws of learning and, in doing so, can contribute at a practical level to large improvements in the effectiveness and efficiency of teaching.\textsuperscript{34} We can also explore new avenues and adopt different metaphors to see where they lead. However, just as reductionist science has achieved awesome success by rigorously testing new theories, any metaphor must be carefully evaluated. It is critically important that we do not degenerate into ‘metaphor wars’ in which some approaches to learning science are dismissed as passé or simplistic just because they have been around for a long time.

In the conclusion of his paper, Regehr suggests that ‘[the science of education] is about exposing our underlying metaphors and assumptions and examining the relative value of these metaphors and assumptions for interpreting the educational issues that we are … trying to address.’\textsuperscript{33} It is in precisely this spirit that the present critique was written. Like scientific theories, metaphors must be validated lest we fall prey to the danger of simply drawing the wrong conclusions.

\textit{Acknowledgements:} none.  
\textit{Funding:} none.  
\textit{Conflicts of interest:} none.  
\textit{Ethical approval:} not applicable.

**REFERENCES**

4 Durning SJ, Artino AR Jr, Pangaro LN, van der Vleuten C, Schuwirth L. Perspective: redefining context in the clinical encounter: implications for research and
Chaos, complexity and complicatedness

27 Neville AJ, Norman GR, Michael G. DeGroote School of Medicine Faculty of Health Sciences, McMaster University. Acad Med 2010;9 (Suppl):624–7.

Received 15 November 2010; editorial comments to author 23 November 2010, 23 December 2010; accepted for publication 11 January 2011

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