Chapter

Classroom as Complex Adaptive System and the Emergence of Learning

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Abstract

Complex adaptive systems (CAS) theory is offering new perspectives on the nature of learning in school classrooms. In CAS such as social networks, city traffic systems and insect colonies, innovation, and change are occasioned through non-linear, bottom-up emergence rather than linear, top-down control. There is a growing body of evidence and discourse suggesting that learning in school classrooms, particularly in the early years and primary phases, has non-linear, emergent qualities and that teachers, school leaders, and educational researchers can gain valuable insights about the nature of interactive group learning by analyzing classrooms through a CAS lens. This chapter discusses the usefulness of a CAS framing for conceptualizing learning in primary school classrooms. It will explore key arguments, discuss relevant objections and draw on my own research to make the case for a measured application of CAS theory to primary classroom teaching and learning, explaining how it can support the development of innovative pedagogies.

Keywords: complexity theory, complex adaptive systems, emergence, teaching & learning

1. Introduction

In this chapter, I discuss primary classroom pedagogy and assert that common portrayals of teaching and learning, particularly in media, policy, and some academic discourse, fall well short of capturing the complexity of what goes on in many classrooms. Traditional depictions of learning as linear, mechanistic, and in direct causal connection to teaching "input" remain dominant across education sectors, despite their failure to explain the unpredictable and uneven topography of pupil learning outcomes. Against this background, I argue that complex adaptive systems (CAS) theory may offer a useful non-linear alternative to the dominant linear, mechanistic thinking which dominates in many conceptions of school learning. In Section 2, I present the challenges and consequences of oversimplified conceptions of teaching and learning. In Section 3, I explain CAS theory and associated ideas in the context of education and explore arguments for and against applications of CAS thinking to classroom learning. In Section 4, I explore some pedagogical implications of conceptualizing classrooms and classroom learning through a CAS lens and discuss what these might mean for teachers.

2. The over-simplification of classroom teaching and learning

There is widespread support in the literature for the view that primary classroom learning and teaching are not straightforward processes. Davis and Sumara [1] note that most teachers will attest to the unpredictability of learners' responses to teaching. Eisner [2] described teaching as "an inordinately complex affair" and others, [3–5] have framed teachers' roles in terms of managing uncertainty and problematizing unpredictability. Shulman [6] is unequivocal in describing teaching as "perhaps the most complex, most challenging, and most demanding, subtle, nuanced and frightening activity that our species ever invented". Descriptions of the facilitation and elicitation of learning by teachers themselves [7, 8] also acknowledge the unpredictable, dynamic and often messy, uneven nature of learning, and Alexander et al. sum up the argument with the assertion that "one cannot begin to understand the true nature of human learning without embracing its interactional complexity [9]." The case for learning and teaching being far from straightforward is also captured succinctly by Schon, who described teachers' work as operating in the "swampy lowlands" of everyday life. For him, "the problems of real-world practice do not present themselves to practitioners as well-formed structures. Indeed, they tend not to present themselves as problems at all but as messy indeterminate situations [10]." Considering this, it seems reasonable to suggest that what pupils learn in the context of school classrooms does not flow mechanistically from teachers' input and is not entirely within the conscious control of either teachers or pupils. This is not to argue that learning is not a function of teaching, but that pupil learning must be driven by more than merely the influence of teachers and teaching. It seems reasonable to hypothesize that teaching input is filtered through a range of networked factors resulting in learning occurring sometimes because of, sometimes despite, and sometimes irrespective of what teachers do.

Notwithstanding these depictions of the complex nature of learning and teaching, including from teachers themselves, a popular portrayal in policy and public discourse runs counter to this, presenting teaching and learning as simple, linear, causal, and mechanistic activities [11] reflecting a technical rationalist view of the profession [12, 13]. In this conception, teachers simply apply instrumental "teaching" solutions to address well-formed "learning" problems. Discourse and national agendas concerning teaching, learning, pupil progress, curriculum, standards, and teacher professional development are typically driven by this input-output conception. In the dominant policy discourse, "outstanding" teaching is often narrowly defined as the meticulous planning of lessons to meet specific, predetermined objectives [14] and despite years of reform in the UK and comparable education systems, the language of policy [15] still partially depicts a transmission and absorption notion of teaching and learning. This leads to the popular notion that if teaching is "outstanding" learning will (or should) be too. Tessellating policies of national testing, league tables, school inspection, and teacher competency descriptors firmly position teachers as the lynchpins [16] of pupil progress with the consequence that they are routinely held accountable for a phenomenon (learning) which appears to be only partially within their control.

This technical rationalist positioning of teaching alludes to an absorption and output conception of learning and learners. However, the pupil end of any learning and teaching relationship is no less complex than the teaching end. In any given school classroom "the persistence of inequities in student achievement [17]" speaks to a range of factors influencing learning. These include inherited and environmental

predispositions such as cognitive ability, personality, confidence, task commitment, and risk-taking tendencies along with influences from home and school ecosystems. More ephemeral factors influencing volition such as social dynamics, nutrition, mood, and even weather may also play a part. Research from several paradigms offers insights into learner factors and their effects on learning outcomes. Bronfenbrenner's [18] Ecological systems theory, for example, presents a framework for describing community and environmental influences on individuals. According to the model, interaction with other individuals and institutions across five levels of systems (from micro to chrono) shapes the individual's growth, learning, and development. These include family, peer group, school, media, and health care policies for example. Research into the emergence of gifts and talents in school-age learners [19, 20] has highlighted common elements, which typically correlate with high performance, including general cognitive ability, environment, personality, self-confidence, and chance. Numerous studies from the field of psychology [21–24] illustrate how personality influences readiness to learn and learning outcomes. Common findings suggest that the long-established "Big Five" personality traits (openness, conscientiousness, extraversion, agreeableness, and neuroticism) interact in statistically significant ways with learning. Studies of class emotion and mood [25–27] reveal how pupil interactions, on/off-task behaviors, and learning can be influenced by interpersonal features including regulation, negotiation, and resistance. Despite wide-ranging acknowledgment across multiple disciplines that learning is influenced by a complex array of converging and mutually interacting factors (those mentioned above and many not mentioned e.g. working memory, self-efficacy, parents' education, personal health, and cultural expectations to name a few), its depiction remains largely characterized in public discourse by the receiving and remembering of information and the mastery of a set of skills. This is evidenced most clearly in the way that policy developments in the United Kingdom, and comparable education systems, over the last 20 years have striven to routinize teaching.

It is against this landscape, in which teaching and learning are characterized quite differently in policy and media to how teachers and pupils experience them, and how research frames them, that this discussion chapter sits. I have previously suggested [28] there is a need for more accurate depictions of teachers' work and its relationship to pupils' learning. As Hardman [29] points out, there has been a failure of simple causal explanations to adequately account for the complexities of school and classroom learning, because, according to Davis & Sumara learning tends to "defy simplistic analyses and cause-effect explanations [1]". Complex adaptive systems (CAS) theories may offer valuable insights about ways that learning emerges in classrooms and my hope is that advancing this discussion will contribute to unpicking current over-simplified thinking about teaching and learning and offer new perspectives on pedagogy.

3. Complex adaptive system (CAS) thinking

A less reductionist, less mechanistic, more accurate depiction of classroom teaching and learning will necessarily acknowledge their complexity. The framework of complexity theory (an umbrella term applied to the analysis of a range of dynamic, non-linear systems) is a transdisciplinary theoretical framework presenting a non-linear, non-mechanistic scheme through which to view change within systems. Emerging originally from disciplines such as computer science, cybernetics, chaos

theory, and the natural sciences [30–32], complexity theory has been applied to the natural sciences since the 1950s, and to the social sciences for approximately the last 30 years, as a tool for understanding systems containing multiple agents (in the case of classrooms: pupils, teachers, ideas, environment) whose adaptation, development or change (classroom system learning) is resistant to explanation using the traditional scientific method, or as Newell puts it, "phenomena resistant to reductionist analysis [33]." Complexity theory breaks with linear, causal, or deterministic explanatory frameworks [34], rejecting a version of reality in which "a knowledge of inputs is adequate to predict outputs [1]". Complexity theory distinguishes between systems that are merely complicated and systems that are complex. Complicated systems, such as clocks or engines, have many moving, interacting parts that behave in centralized, repetitive, predictable ways. They remain consistent over time. In contrast, complex systems display less predictable, bottom-up, emergent, and non-linear behaviors, because the elements constantly and mutually affect one another [35]. Central to the behavior of complex systems (and therefore to this discussion) are the concepts of self-organization and emergence. Complex systems are said to have self-organizing properties, meaning that they are not centrally governed or controlled, instead of individual agents in the system act with degrees of autonomy, through local decision-making. From these autonomous actions patterns of coherent, aggregate behaviors form across the system from the bottom-up; this is referred to as emergence. My contention in this chapter is that to some extent learning can be said to have emergent qualities and that complexity may provide a framework for depicting and explaining elements of classroom learning which are routinely omitted by mechanistic portrayals of classroom teaching and learning.

Complexity theory has been employed as a lens through which to analyze systems in and of education for a little under three decades now exploring a range of aspects including curriculum [36–39], educational research [1, 40–42], purposes of schooling [43], educational change [44, 45] and the philosophy of education [46]. A limited range of empirical studies have been undertaken into areas including school interventions [47], non-linear modeling for education systems [48, 49], and agent-based studies at system, school and classroom levels [50–52]. Since complexity theory is still a novel framework in education, support for the application of a complexity lens to classroom learning is currently limited but growing. A number of studies have examined classrooms, focusing on links between classroom systems and complexity characteristics, analoging pupil interactivity with the non-linear, ensemble agent behavior characteristic of complex systems. My justification for framing the primary classroom as complex draws on these accounts which suggest that complexity has useful applications in the analysis of classrooms and classroom learning.

Systems that adapt themselves through complex emergence are described as complex adaptive systems (CAS). Typical examples from the natural sciences include ant colonies, insect swarms, or clouds, and city traffic is an example often cited from the human social sciences. In each case, patterns of complex aggregate behaviors emerge through the mutually self-interested actions of individual agents following simple rules. The system "learns" and adapts itself through the network of agent interactions without top-down control from any central authority. CAS is said to function more bottom-up than top-down. Whilst descriptions of CAS properties in the literature across multiple domains overlap considerably, the lack of any unified CAS field of study, a single body of literature, or agreed nomenclature has proved an impediment to achieving a universally applicable framing in the social sciences. As Sullivan points out, "it seems every theorist has his or her own list of characteristics, qualifying

properties, or optimal conditions for complex adaptive systems, each slightly different from the next [53]". Some have attempted to consolidate divergent definitions into more generalizable interpretations for CAS [53–58], however, even in synthesized forms, there is a considerable divergence from one framing to the next. Some theorists [1, 29, 33, 40, 44, 46, 53, 59, 60] have drawn on framings from complexity sciences to describe and discuss features of CAS in the field of education, though here too, no consensus exists about how to frame CAS.

The question of whether a school classroom is a CAS has been studied and discussed by some [29, 53, 59] including me [61] with mixed, but indefinite, conclusions, which depend largely on the CAS definition used and the organizing principles at work in the classroom. I have previously acknowledged [61, 62] that a primary classroom is not a CAS as originally conceived in the natural or computational sciences. However, along with others, I maintain that classrooms have sufficient CAS-like characteristics to warrant using a CAS framing to seek otherwise tacit insights about the nature of classroom learning. The most significant voices concerned with CAS thinking and education (Davis [1, 63, 64], Sumara [1], Mason [44, 45], Morrison [46], Sullivan [53] to name some) agree that caution should be exercised when attempting to conceive of the school classroom as a CAS, or equating emergence with learning. Analogies were taken from complexity science on radically emergent systems, for example, insect swarms, suggests that a classroom organized along similar principles would maximize knowledge sharing between pupils, have little by way of top-down leadership, prioritize individual self-interest and investigate questions to which neither pupils nor teachers know the answer. This is contrary to how most classrooms operate, whereby teachers exercise central executive control, pupil to pupil knowledge sharing may be considered cheating and the teacher tends to know "the answer". Whilst complexity offers "intriguing and generative metaphor(s)" for the classroom system [33], there are obvious limitations to such analogies. Despite some reservations, however, there is agreement among those who have examined learning through a complexity lens (Davis [1, 63, 64], Newell [33], Sullivan [53], Hardman [29] in particular) that instruction alone does not cause learning and that there are, as yet unearthed insights about learning which a CAS framing may elicit.

Whilst no two definitions of CAS in the literature align exactly, there are certain characteristics I deem to be most relevant to school classrooms that appear repeatedly in CAS definitions, shown in **Table 1**. These form the core framework for this discussion of emergent learning. Based on these criteria, a complex adaptive classroom system is one containing multiple autonomous, interacting pupils, whose inter-relationships create networked, self-organized, non-linear behaviors from which change (learning) emerges at different levels (individual, small groups, whole class).

3.1 The idea of a complex adaptive classroom

Complexivist educational researchers have explored ways in which characteristics of school classrooms overlap with descriptions of CAS, pointing out strengths and weaknesses in the comparison. Burns and Knox [65] compared De Bot et al.'s [66] descriptions of the development of complex systems over time, with their own analysis of classrooms. They found a number of correlations, including that both consists of sets of interacting variables (pupils, teachers, resources, environment), both had unpredictable outcomes (learning outcomes, critical incidents), both are part of and connected to other systems (family, institutional, community), both are sensitive to initial conditions, meaning that small changes or incidents can result in

CAS criteria	Definition
Self-organization	Individual agents acting with sufficient autonomy to determine their own actions/interactions/behaviors
• Pupil autonomy	
• Well-networked interactions	
• Local decision-making	
• Impulsive/instinctive behaviors	
Emergence	Organized patterns of synergistic behaviors which aggregate bottom-up across the system as a result of agent self-organization
• Bottom-up behaviors	
• Bifurcations	
• Perturbations/injection of novelty	
• Unpredictability	
• Evidence of non-additive learning	
Non-linearity	Information moves between agents via feedback loops and signals, therefore causality is not linear but networked and recursive
• Causation networked	
• Information moves back and forth between pupils	
• Pupils send and receive signals	
Transcend their components	Exhibit properties not manifest in individual agents; systems that learn; learning is more than the sum of the system parts
• Produce learning beyond the knowledge/ capabilities of each individual.	

Table 1.
CAS characteristics salient to classrooms and classroom learning.

large differences over time and both develop through interaction and through internal self-organization. These qualities produce the inherent instability which predisposes classroom systems to emergent change over time. Davis and Sumara [1] posit that to really understand the dynamics of the classroom it is necessary to stop thinking linearly, a point which is supported and explained, with reference to how the social world behaves, by Byrne [67] who asserts that outcomes are determined by multiple causes moving in non-linear ways. Typical classroom examples of this are the multiple factors that might determine whether a pupil contributes verbally or not to a class discussion. These might include (though are not limited to) peer pressure, personal ambition, knowledge of an answer, fear of failure, confidence level, social status, degree of interest, or desire to go to lunch. If the classroom is a CAS, one would also expect these factors to interact with one another and exert influence over other pupils indirectly ("if my neighbor keeps quiet I will speak up/keep quiet; if my neighbor speaks up I will compete to speak first/keep quiet") making causality non-linear, an argument which most teachers would not find it difficult to make. The point here is that classrooms consist of more than simply 30 separate linear interactions between teachers and pupils. Pupils influence one another in multiple visible and invisible ways making it difficult to trace the antecedent(s) of any given event or outcome.

Arguing that classrooms display CAS behaviors, Guanglu [68] points to the non-linear, recursive nature of teaching and learning, in which pupils' and teachers' interconnections produce continuous recursions of understanding, interpretation, re-understanding, and reinterpretation. Teaching and learning do not always follow

this pattern, in fact, the linear transmission of information remains common in many classrooms and arguments for more direct instruction are currently strengthening [69–71]. However, some degree of openness and randomness are characteristic of even in the most tightly controlled classrooms and at times learning can take on forms more akin to "mutual fertilization, pollination [and] active catalytic(s) [38]". Guanglu suggests that this mutuality is seen in the experience, commonly reported by teachers, of gaining a new or better understanding of the subject matter they are teaching, through the act of teaching it [68]. Support for conceptualizing school classrooms as CAS also comes from Hardman [29] who asserts that sudden or unanticipated emergence of novel outputs in classroom activity is inevitable, partly due to the internal diversity of classrooms, including the uniqueness of individual pupils' (and teachers') brains. Novelties might include sudden realizations, moments of inspiration, original ideas or solutions derived from collaborative experimentation. Diversity is a theme which Davis and Sumara [1] pick up. They suggest that differences, counterpoints, and asymmetries between agents within a system cause the very perturbations from which self-organization and emergence originate. Diversity in this sense does not refer to demographic identity differences (race, gender, etc), but to the myriad tangible, intangible, perceptible, and imperceptible differences which exist between human beings which in the classroom may cause differences in perspective, motivation, intent, action or utterance. These might include, personality traits, personal histories, family environment, inherited traits, self-esteem, self-confidence, or mood. In a CAS, internal diversity is one factor that helps maintain a system's vibrancy and promote adaptation, keeping it far from equilibrium. In the context of a primary classroom this is seen in the way that given sufficient autonomy, pupil interactions rarely follow prescribed pathways or result in predictable outcomes. Collisions between individual diversities create collisions between ideas and perspectives which in turn creates the pluriform, entangled messiness so evident to teachers. From the mess, however, novelty and innovation often emerge.

A few suggestions are evident in these descriptions which lend support to the framing of classrooms as CAS. Firstly, that classrooms, like other CAS, have many moving parts which, given sufficient opportunity to interact, will produce productive instability. Secondly, that instability is causally connected to learning insomuch as randomness changes interactive behaviors and injects novelty, which can qualitatively change learning states. Thirdly, there is an implication that even in classrooms characterized by linear transmission and high degrees of centralized teacher control, openness is inevitable to some degree. Described in these accounts of classrooms and adding some legitimacy to comparisons with descriptions of CAS, are factors beyond, or resistant to, control. Despite the structure of organized schooling, the structure of the curriculum, and the necessary order imposed by teachers, diversities reveal themselves when pupils enjoy sufficient autonomy and openness in the classroom system and this creates opportunities for unpredictability and non-linear change. An example of non-linear emergent learning is evident in the common understanding that alongside the top-down influence of the teacher, pupils also influence and change one another through mutual self-influence [63]. The flow of content, explanation, and questioning does not only travel unidirectionally from teacher to pupils and result in the development of neat predictable knowledge, understanding, and skills. Alexander et al. point out that "change that happens in the learner, be it dramatic or imperceptible, or immediate, or gradual exerts a reciprocal effect on the learner's surroundings [9]". This depiction offers a strong positive comparison between classrooms and CAS, implying that there is also a flow of information and influence

between pupils, towards the classroom environment and climate and, presumably, back towards the teacher as well. This suggests that as pupils change, they also change one another, the teacher and their surroundings, including the environment, through their mutual interconnectedness, much like the behavior of a CAS. Davis and Sumara refer to this phenomenon when stating that complex systems, such as classrooms, are systems that learn. Within such systems, they suggest

> *"one cannot reliably predict how a student or a classroom collective will act based on responses in an earlier lesson, or sometimes a few minutes previous. In other words, strict predictability and reliability of results are unreasonable criteria when dealing with systems that learn." [1]*

This means that in a classroom, change (learning) is unlikely to only unfold entirely as intended or directed by the structures of organized schooling, the curriculum, or the teacher. The system and its constituent agents will also adapt and change in ways not predicted or intended by those governing structures. This is evident in the common occurrence of classroom ethos, culture, and atmosphere changing over the course of a week, month, term, semester, or academic year. Such changes are behavioral, relational, environmental, and knowledge-based and can be felt by pupils and teachers in the dynamics of the classroom system. The system adapts because the collective adapts. Groups adapt because individuals adapt. Haggis suggests that emergence is always unpredictable to some extent, stating that "what emerges will depend on what interacts, which is at least partly determined by chance encounters and changes in environments [41]." This supports Biesta's point [72] that learning cannot be reliably predicted but is a retrospective judgment. A principal learning characteristic of classrooms according to complexivists is their tendency towards self-organization and self-maintenance, what Sullivan [53] refers to as "adapt[ing] of their own accord." Some degree of self-organization is inevitable in any system which is not entirely mechanistic and deterministic and since wholly determining the opinions, predilections, desires, impulses, thoughts, and behaviors of groups of pupils is impossible (not to mention undesirable), the tendency for self-organization to exert an influence on classrooms is understandable.

3.2 CAS classroom framing: Some cautions and discussions

It is necessary to ask, however, to what extent this phenomenon can be said to positively influence learning. In a CAS such as an ant colony, immune system, or decentralized finance block-chain, the self-organization and its concomitant adaptation is the learning. The fluctuation and interaction of many agents (be they ants or genes) all influencing one another, all influencing the system and being influenced by it, produces change that exceeds the individual possibilities of the agents. However, this analogy does not translate perfectly into school classrooms because, as Biesta [72] points out, education is not a morally neutral activity, but a purposeful, values-orientated one, and because of this, what is learned matters. He argues that describing learning as whatever emerges as a result of classroom interactions ignores the fact that education exists so that people learn something, not just anything. This argument fits with assertions from others [42, 73] that a CAS framework has considerable limitations when analyzing classroom learning because classroom learning is goal-orientated and has prescribed directions in which teachers must steer all pupils. As Kuhn puts it

> *"It may be argued that there is a fundamental mismatch between complexity and educational enterprise as in essence complexity is descriptive whereas education is normative, or goal-orientated. {…} complexity offers organizational principles for describing how the world and humans function. Education, however, is orientated towards achieving certain goals [42]."*

These descriptions of the purposes of education are demonstrably incompatible with depictions of CAS, in which higher complexities may emerge as a consequence of agents operating individually out of mutual self-interest. Kuhn goes on to state "complexity merely describes, whereas education aims to make a difference [42]". A consequence of this purposefulness that characterizes education (and which distinguishes it from learning in the general sense) is the centralized control of the teacher. Teachers impose expectations and structures on classroom activity and do so in the interest of curricular aims and purposes. Biesta [72] describes how this introduces "an asymmetrical element into the educational process" which is "one of the main reasons why educational learning is radically different from collective, interactive, explorative learning". Without the imposition of purposive structures, the likelihood of emergent learning aligning with curriculum aims is low and the risk that nothing of curricular value will be learned, potentially high. Individuals in a classroom system are not all equal and teachers do not permit pupils to behave out of self-interest, for good reason. Ramussen agrees that educational learning has "special intentions in mind" [74], describing teaching as a "social arrangement and organization aimed at intensifying possibilities for learning and the results of learning". The absence of any overarching "special intentions" in a CAS found in nature or in human systems at a great scale, such as cities or economies, weakens the case for classrooms being viewed as CAS. Sullivan's study [53] illustrates this. Examining three different lessons (a music class, a mathematics class, and an English class) through a CAS lens, he noted that not all the classrooms displayed complex adaptive behaviors. He suggests that a key factor in whether a classroom can usefully be classified as a CAS is whether adaptations within the system are triggered by the teacher or by the collective. If the teacher orchestrates all or most responses to daily events (snow days, timetable changes, pupil absence) with little involvement from the pupils, then adaptations cannot be described as bottom-up. In concluding he states

> *"One may say that classrooms are inevitably complicated, and I would certainly agree. One may even say that all classrooms exhibit some measure of complexity, and I might agree. To assume, however, that a class will network itself in such a way that it adapts in any meaningful way is too much to assume [53]."*

Radford [40] bridges arguments for and against comparisons between classrooms and CAS using a metaphoric continuum between what he refers to as "clockishness" and "cloudishness". He draws on Popper's assertion [75] that all systems can be viewed on a continuum between deterministic, reducible, and predictable (clockish) on one hand, and indeterminate, unpredictable, and open (cloudish) on the other. Radford's contention is that even the most deterministic systems, such as clocks, have degrees of unpredictability, and that likewise, the most open and unpredictable systems, such as clouds, have some degree of predictability. Viewed at sufficient resolution, a clock will reveal its lack of mechanistic causality and a cloud will reveal its causalities. All phenomena, according to Radford, can be thought of as having degrees of both "clockishness" and "cloudishness". The question is, which is the most useful or accurate explanatory framework for depicting a given system. Some researchers have attempted to describe

the "cloudish" features of classrooms and how exploring them might lead to new insights about classrooms and classroom teaching and learning. Semetsky for example presents a radical vision of a self-organized classroom, characterized by decentralized control, pupil autonomy, and an absence of direct instruction. She posits that this would "naturalize the concept of learning [76]" through the introduction of greater choice for pupils. She envisages a classroom in which there are no right or wrong responses or answers, just an array of choices for pupils, creating an environment with an "inherent incapacity for students to experience failure at any point within the process" because there is no "special educative aim". This vision of classroom learning is considerably more cloud-like than clock-like and would require a radical overhaul of curriculum structures, not to mention the very purposes of education. Semetsky acknowledges that this radical vision has the potential to be counter-productive, however. She draws on Cillier's warning about chaotic system behaviors or "catatonic shutdown [77]" and suggests that a multiplicity of pupil options may contribute to complete disorganization rather than self-organization. This is similar to Waldrup's assertion that whilst frozen (clockish) systems can benefit from "loosening up a bit", turbulent (cloudish) systems "can always do better by getting themselves a little more organized [78]".

Morrison presents a similar critique and asks

> *"whether self-organization is such a good thing, or whether it will lead to diversity, inefficiency, time-wasting, mob rule, and a risk of people going off in so many different directions that the necessary connectivity between parts of an organization, its values and direction will be lost or suffocated [46]."*

This is a valid question. Judging when sources of novelty and disruption risk undermining sources of coherence within a system is crucial to maintaining a productive edge of chaos states and is a crucial aspect of teacher professional judgment. In a CAS such equilibrium is maintained through self-organization. In a classroom, it is largely due to the influence of the teacher. A key illustration of why the conception of classrooms as CAS both is, and is not, accurate and useful.

Others present visions of classrooms as self-organizing adaptive systems, which are less adversarial to the purposes of education than Semetsky's. Fong for example, suggests that the concept of self-emergent order is well suited to early learning environments because of their natural tendency to balance the "dual worlds of emergent order and imposed control [79]" and the challenges teachers face in managing the latter in busy nursery or kindergarten classrooms. Sullivan [53] also takes a positive view of the classroom as a CAS and posits that in classrooms where the features of CAS such as self-organization, distributed control, and agent-interaction (the more cloudish characteristics) are maximized, novel learning emerges. Defining emergent learning as the "acquisition of new knowledge by an entire group when no individual member possessed it before [53]" Sullivan suggests that some curriculum subjects lend themselves more than others to the conditions in which such learning might emerge (literacy more so than mathematics in his example). One such feature of CAS which might be emphasized and capitalized upon in the interest of classroom learning is neighbor interactions. In their study of Canadian mathematics teachers Davis and Simmt noted that with sufficient density of short-range pupil interactions and networking, the emergence of novelty was likely. Their concept of neighbor interactions includes, but also stretches beyond, pupils sitting on the same table. They emphasize that "neighbors in a knowledge-producing community are not physical bodies or social groupings. Rather, the neighbors that must "bump" against one another are ideas [63]". They recommend

maximizing conditions in which pupils' ideas can collide, not just between neighbors on tables, but across the topography of the classroom system, because "agents within a complex system must be able to affect one another's activities [1]".

It is clear that school classrooms share several characteristics with CAS, however, the extent to which any classroom can usefully be described as complex depends on how it is organized. Classrooms that operate under strictly centralized control ("clockish") will share fewer features of CAS, whereas classrooms which function in more decentralized or distributed ways ("cloudish") are likely to create space for the sort of autonomy which invites more CAS-like behaviors. Under such organizational principles, pupils may interact in networked and non-linear ways, becoming self-organizing, and inviting learning to emerge bottom-up, rather than always traveling top-down from the teacher. **Figure 1** depicts three broad typical organizing principles

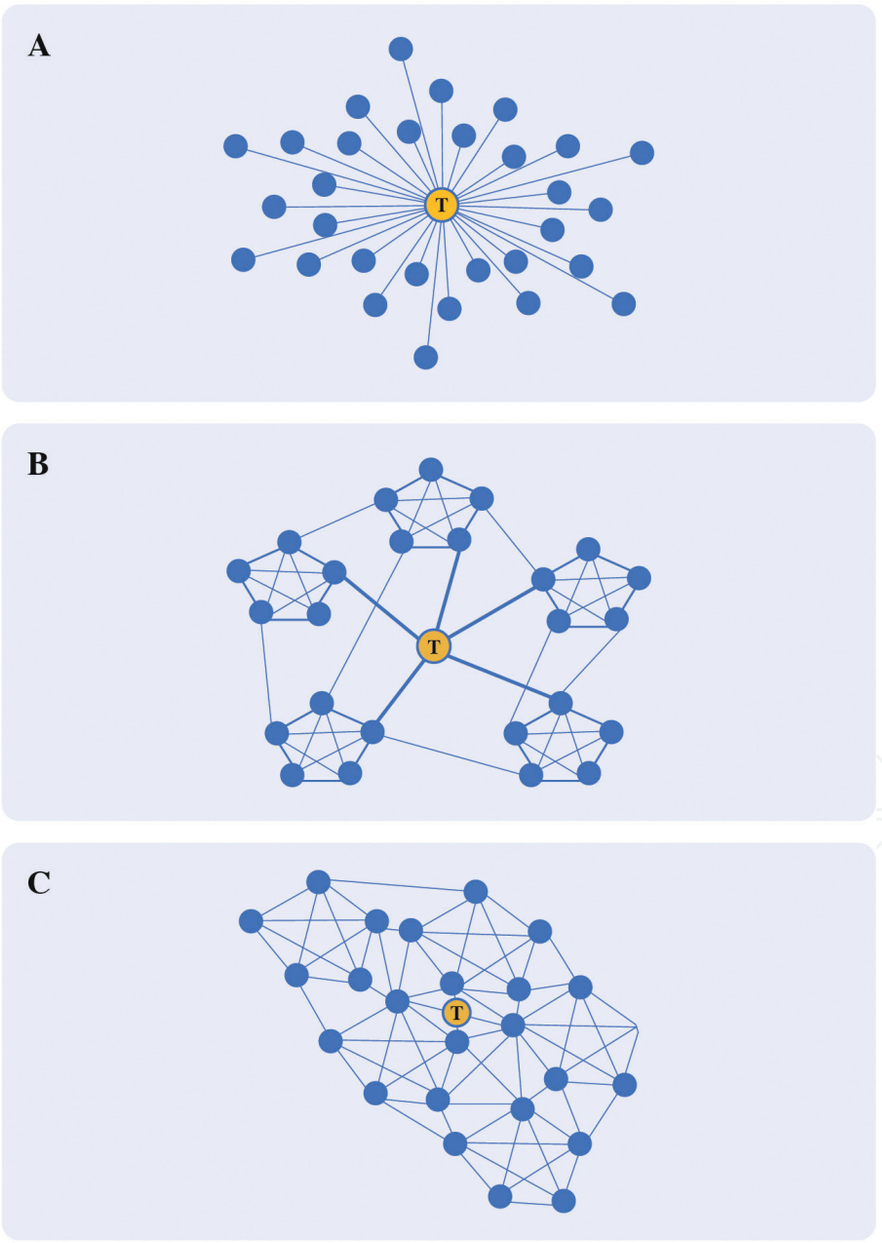

Figure 1.
Centralised [A], decentralized [B], and distributed [C] classroom organizing principles. Adapted from Davis and Sumara [1].

common to many classrooms: centralized, decentralized, and distributed. When centrally organized [A], communication flows linearly from the teacher to the pupils but there is little or no interaction between pupils. When organized in a distributed manner [B], groups of pupils interact, including with the teacher, however, there is little or no mutual interaction between pupil groups. In a more distributed organization [C], interactions occur between any individuals with no central organization from the teacher. Newell [33] points out that all three organizational principles may be enacted at different times in any given classroom (even within a single lesson). In classrooms where decentralized or distributed forms are common, ideas are more likely to collide, pupils are more likely to become mutually influential, novelty and innovation may be more apparent, and learning may emerge which exceeds what any individual pupil previously knew or understood.

However, as Semetsky [76] has noted and my own research [62] attests, events, occurrences, and interactions that challenge or obstruct learning are also more likely in decentralized and distributed classrooms structures. With greater pupil autonomy comes greater unpredictability, greater likelihood of social conflict, and greater unevenness in pupil participation. Many theorists [80–87] have also noted that pupil interaction alone rarely results in elaborated learning and that the organizing and structuring influence of the teacher is essential in transforming pupils' hunches and intuitions into knowledge and understanding. With this in mind, and notwithstanding the evident CAS-like qualities of classroom learning, it is relevant to ask what the potential pedagogical benefits of a CAS classroom framing might be.

4. Implications for teachers and teaching

Notwithstanding its limitations, there is sufficient merit in the arguments for CAS-classroom comparisons to conclude that viewing the classroom through a CAS lens can illuminate a range of teaching and learning behaviors that might otherwise go unnoticed, and therefore unattended to. Among the drawbacks to an over-simplified, linear view of teaching and learning mentioned in part one of this chapter, is the risk that despite knowing better, teachers may teach in ways that presume a linear relationship between teaching and learning, missing opportunities to set conditions conducive to non-linear emergence. A CAS lens may encourage teachers to think non-linearly about learning processes, to become more attuned to collective, networked effects on learning, to see the critical potential in moments they might otherwise ignore, dismiss or want to prevent, and gain a more thorough appreciation of why pupil learning does not appear to augment in a steady trajectory. Arguments have been made that the extent to which classrooms reflect CAS-like qualities depends on how they are organized. More centralized organizational structures are less likely to encourage self-organized behaviors, whereas decentralized or distributed structures are more conducive to self-organization and emergence. In this final section I argue that teachers can occasion emergence through the organizational principles they employ and the degrees of autonomy they give to pupils, in order to capitalize on useful CAS-like classroom characteristics in the interest of learning. Part four draws on preliminary findings from my own recent research into emergent learning in a British year 4 classroom to explore how this might be achieved and what the benefits might be.

4.1 Thinking non-linearly

Linear thinking tends to result in linear expectations, which for teachers means the assumption that tangible evidence of pupil learning will follow shortly after teaching input. This mechanistic reckoning about learning is a key part of the simplification problem presented at the start of this chapter and is ubiquitous in classrooms across the world. However, it does not reflect how many teachers experience classroom learning on a day-to-day basis. Thinking non-linearly about teaching and learning means understanding that learning is a consequence of multiple, networked factors which may not covary linearly or occur in the same moments or places. Learning, when it emerges tangibly, is the result of inputs from multiple sources, including direct teaching, autonomous activity, peer influence, social dynamics, personality traits, prior conceptions, understandings, misunderstandings, environment, and chance, from a range of temporally diverse events. In short, learning (including individual learning) results from system-wide factors, not simply the linear mechanisms of teaching. Instruction may be the dominant influence on pupil learning, but is far from the only influence and its effects are filtered through multiple influences both within, and outside of, the classroom system. Awareness of the networked and recursive nature of learning enables teachers to notice, attend to and even plan for the pluriform influences which may assert themselves in, and beyond, the classroom. For example, awareness that pupils' mental models, their understandings, and the connections they make are substantially influenced by experiences outside of school may lead a teacher to elicit information about pupils' wider experiences of a phenomenon before planning to teach it. Similarly, knowing that new knowledge may emerge through decentralized and distributed interactive structures may lead teachers to facilitate episodes of autonomous, or semi-autonomous group activity expecting pupils to create or evolve ideas which they themselves had not planned for. Thinking non-linearly can encourage teachers to not only ask conditional "if-then" questions about teaching and learning but also consider "what if …" questions which can produce sensitivity to teachable moments. Thinking non-linearly changes expectations about how, when, and from where learning might emerge and can result in teachers noticing potential and future learning in its infancy. Sensitivity and responsiveness to "soon-to-be" learning as it appears are at the heart of effective pedagogy. Understanding that pupils, their ideas, utterances, moods, similarities, differences, and personal histories interact in non-linear ways can help teachers to look for potential learning in places and at times not typically explored when expectations follow singular, linear logic. This includes finding learning, or the conditions for learning in unlikely places, including classroom disruption, in social conflict, or in incidental, unintended moments.

Thinking non-linearly is not a typical habit for most teachers, however, trained as they often are to view teaching and learning in a unidirectional causal relationship in which learning is singularly the product of teaching. This is essentially the central presumption of the "what works" educational paradigm [88] and there are understandable justifications for this habit of mind; not least because it is accurate to some extent. Learning is a consequence of teaching. The problem is not that teaching has no part to play in learning, it plays a significant part, of course. The problem is the failure to understand teaching and learning as existing in a recursive, mutually influencing relationship and failure to see learning as an emergent phenomenon that surfaces because of bottom-up dynamics as much as from top-down instruction. Non-linear

thinking, which attempts to accommodate these concepts, will require some effortful reimagining on the part of teachers well-versed in the "what works" paradigm.

4.2 Attunement to networked influences on learning

Non-linear thinking about teaching and learning has the potential to unlock awareness of the different sources which influence learning and how they interact with one another. Once aware that instruction is only one of several influences and that the multiple influencing factors are mutually interactive, teachers may view common classroom scenarios and occurrences differently. For example, when pupils articulate their understanding of a concept or process it is likely that the new understanding was constructed in an uneven trajectory involving bursts, plateaus, and stops over time. In addition to teaching input, the conceptual understanding will be a result of their interactions with other pupils, the collision of ideas those interactions permit, interaction with the environment and with aspects of their own and others' personalities, learning habits, social status, intellectual and non-intellectual pre-requisites. Sensitivity to these factors can support teacher judgments about pupil grouping, sequencing, and duration of classroom activities, whether and when to intervene, scaffolding questions to ask, and the importance of helping pupils to link experiences. My research with 8 and 9-year-old pupils in a British Year 4 classroom [62] suggests that learning is always a process of organizing, reorganizing, constructing, reconstructing, and refining existing knowledge and understanding. This was illustrated in instances where pupil learning was the consequence of errors and misunderstandings, off-task as well as on-task behaviors, and because of, rather than in spite of, social conflict. There was also evidence that asymmetries in pupil social hierarchies produced discussion and knowledge sharing which more symmetrical dynamics almost certainly would not have. In one such example, the disruptive influence of one pupil in a practical small group activity and the frustration it caused other group members actually drove reconfigurations in pupil roles and articulation of perspectives, arguments, and explanations. The atmosphere was not calm and cooperative, but ideas, demonstrations, and later articulation of learning almost certainly resulted in part because of this. Behaviors which a teacher might instinctively want to prevent unlocked learning for some pupils, to some extent. Attunement to these factors and possibilities, particularly the knowledge that learning can emerge out of social conflict (which teachers routinely, and understandably, aim to suppress) has the potential to shift teachers away from expecting evidence of learning during or shortly after instruction, towards a more authentic appreciation of and attention to the range of antecedents, including unexpected ones.

4.3 The unexpected emergence of learning

Attunement to the CAS-like features of classrooms and non-linear thinking about learning processes opens the door for teachers to re-evaluate their intuitions about where and how learning can, or might, emerge. Acknowledging that some antecedents of visible learning originate from outside of the linear mechanisms of direct instruction means acknowledging that learning is caused and supported by more than simply teacher explanation and demonstration or planned classroom activities. It may also emerge incidentally during the non-lesson time or out of instances of social disruption, which teachers typically aim to discourage. Evidence from numerous classroom studies [89–93] suggests that when pupils collaborate autonomously, or

semi-autonomously, on shared activities some degree of social conflict is inevitable. This may range from minor disagreements about turn-taking or resources that do not interrupt the flow of activity, to larger arguments that disrupt purposeful activity, cooperation, and group productivity. What these studies do not acknowledge, however, is that whilst there are sound reasons to discourage an atmosphere of conflict in the classroom, clashes of personality, asymmetries of social dominance, disagreements about pupil roles, and the socially engendered necessity to resolve these can actually produce moments of novelty, innovation, knowledge sharing or motivation which lead to learning. It is no surprise that nowhere in the literature is there any support for the idea that social conflict might also support curriculum learning in unexpected ways, however, some of the data in my recent research [62] suggests that learning does not just survive episodes of social conflict, but can be occasioned by it. I am not here advocating a laissez-faire approach to classroom management or an "anything goes" attitude to pupil behaviors. Calmness, cooperation, and mutual respect are necessary and desirable qualities to encourage in classrooms. However, I am (somewhat tentatively) suggesting that when teachers suspend, even temporarily, their linear expectations about what produces learning (and perhaps even stop thinking about learning as a product altogether), they may notice teachable moments worth capitalizing upon in some unexpected places.

According to Davis and Simmt [63] the network of mutual self-influence between pupils, environment, and classroom climate, and the resulting randomness, opens the door to novel moments of teaching and learning. An example of this in my recent research included instances in which arguments between two pupils prompted periods of increased productivity and "on-task" behaviors from others. In another example the repeated ignoring of a low social status pupil by his small group caused him out of frustration to share his ideas with the teacher, resulting in him eventually explaining it to the whole class, whereafter most groups adopted his ideas. The learning in these incidents, or the conditions for it, emerged bottom-up rather than top-down. What emerged was a consequence of the situated, unique dynamic choreography of multiple pupils' wills, personalities, social standing, and knowledge states, among other factors. Sensitivity to the ways these and other factors can interact to produce conditions for learning where one might not expect to find it can be advantageous to teachers. How then might teachers use this knowledge and capitalize on it in the interest of learning? The knowledge that whilst excessive pupil autonomy, interactive license, or social conflict is likely to obstruct learning, appropriate degrees of freedom from centralized teacher control can invite novelty, could lead teachers to re-evaluate their centralizing instincts and look for a balance between Radford's "clockish" and "cloudish" organization [40] in their classrooms. Such re-evaluations can lead to teachers pausing, observing, and assessing for potential teachable moments. If there are potential benefits in allowing social conflict to play out, enabling pupils to find their own resolutions, this may lead teachers to re-assess how and when they intervene. Judging the line between tolerable and intolerable degrees of social conflict or noticing signs of potential learning benefits is unlikely to be easy, however there is evidence, albeit tentative, that there may be payoffs for teachers brave enough to try. The "edge of chaos" [1] will always be a double-edged sword, inviting innovation but also risking havoc. Semetsky [76] acknowledges that radical visions of open and unrestrained classroom systems, whilst opening doors to possibility, might also be counterproductive. Accepting that interactive learning is by nature open and generative (and therefore susceptible to disorganization), Biesta [72] has argued in favor of enabling constraints, structures which facilitate autonomous pupil interaction,

encourage novelty and originality but without courting havoc. A useful question for teachers therefore might be, how can I implement limits on interactive learning which unlock and enable, rather than dampen, novelty and originality?

4.4 Occasioning emergent learning

CAS-framed classroom research and discussion [33, 61, 62, 64] suggests that CAS-like behaviors do not necessarily occur naturally in all classrooms, but depend to a large extent on balance between sources of coherence and disruption; between centralized control and decentralized autonomy. Having looked at some of the opportunities which CAS-like behaviors might offer teachers and pupils in pursuit of learning, it is worth considering ways teachers might occasion emergence by locating and exploiting "sweet spots" between rigid order and all-out chaos; in which pupils benefit from what autonomous interaction and teacher scaffolding have to offer. This is what Radford [40] refers to when describing systems, which are a balance between "clockish" and "cloudish". This would include knowing how, and judging when, to centralize or decentralize the organization and autonomy, and understanding the consequences. Much like a jazz leader, knowing when to allow improvisation and when to return the ensemble to the main theme. "Sweet spots" exploit the most useful products of centralized, decentralized, and distributed classroom structures, whilst avoiding the unproductive excesses of each.

In tightly controlled, centralized classroom structures ideas tend to flow linearly from the teacher to the pupils and back from individual pupils towards the teacher. Under this organizing principle, ideas do not collide, they simply travel along straight lines, often in just one direction emanating from the teacher. Those ideas become known by everyone but are not interrogated, trialed, experienced, regurgitated, or challenged. The principal casualty of this tendency in highly centralized classrooms is the cross-fertilization of pupil perspectives and emergent learning. Newly emerging understandings, partially articulated thinking, and challenge to pupil assertions tend to arise more freely in distributed peer-to-peer interaction than in centralized, didactic scenarios. Too much centralized communication is likely to stifle this "soon-to-be" learning. At the opposite extreme, in classrooms principally characterized by distributed structure, ideas tend to collide but are rarely refined, sustained, or linked coherently. The main casualty here is the spread of ideas since ideas tend to remain local, petering out without dissemination, and coherence, because thinking remains atomized. Somewhere between these extremes lie sweet spots where pupils experience sufficient freedom and autonomy to encourage elements of self-organization and bottom-up novelty, accompanied by sufficient central teacher coordination for emerging ideas to be shared, digested, shaped, and sustained. Factors that teachers can manipulate to locate such sweet spots include (among other things) physical space, time periods, activity types, and groupings. Activities with sufficient openness undertaken for appropriate durations by autonomous or semi-autonomous pupil groupings with considered classroom organization and sensitive teacher intervention have the potential to create space for novelty, creativity, and innovation to emerge. Timely shifts between distributed, decentralized, and centralized structures may enable learning to emerge and progress from emergent states towards elaborated, more secure states from which it can be more easily redistributed.

In order to create conditions in which partially formed ideas may grow into articulated explanations or productive applications, a range of pedagogical prerequisites are necessary, beginning with an understanding of what centralized,

decentralized, and distributed modes of classroom organization offer the pursuit of learning. Confidence and competence in noticing signs that classroom structures need to be loosened or tightened follow logically from this, along with knowing how and judging when to do this. Creating open learning activities and opportunities that are fertile ground for ideas to collide, which are encouraging autonomous interaction and structured sufficiently to elicit novelty and originality, whilst avoiding excessive teacher control takes courage and practice. The starting point, surely, is sensitivity to potential teachable moments, attunement to the networked interacting influences at work in the classroom, and openness to the possibility of learning emerging from unexpected places.

5. Concluding thoughts

In response to the widespread tendency for teaching and learning to be depicted in over-simplified and linear-causal terms, this chapter has discussed the potential usefulness of applying a CAS framing to the primary classroom. I have sought to begin addressing the question of whether viewing classrooms as complex systems may illuminate inherent complexities of learning and ask whether doing so reveals any useful lessons for teachers. Descriptions of the behavior of CAS and consideration of the typical characteristics of many classrooms leave little doubt that classrooms have CAS-like features, though the extent to which such features may prevail in any given classroom depends to a large extent on how teaching and learning are organized. The most salient CAS qualities inherent to primary classrooms are occasioned by pupil autonomy, interconnectedness, and interaction through which there is some evidence that learning can reveal itself in emergent forms, more as a consequence of bottom-up than top-down initiative. Under the right conditions, including sufficient enabling constraints and pupil autonomy, a focus on CAS characteristics can draw teachers' attention to the possibility of learning emerging from unexpected sources and in unanticipated times and ways. These include pupil errors, social conflict, and apparently off-task behaviors. However, more research is needed into the forms and value of such emergent learning, including how and to what extent it can be encouraged by thoughtful, imaginative, and sensitive teaching.

A possible implication for teachers is a recommendation to introduce subtle shifts in thinking about classroom practice and pupil learning. This would include considering the potential benefits of loosening central control and allowing pupils sufficient autonomy for self-organization to materialize, holding less tightly to evidence of pupils meeting learning objectives in unitary packages, and developing sensitivity to what else might be learned, when and how. I would urge my fellow teachers away from framings that locate learning as merely the linear product of teaching and instead invite them to adopt a more open and speculative mindset, exploring and investigating pluriform and interconnected antecedents of learning, rather than expecting it to appear as a product following teacher input.

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