Describing mathematics departments: The strengths and limitations of complexity theory and activity theory

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This paper draws on two studies of mathematics departments in 11-18 comprehensive maintained schools in England to compare and contrast the insights provided and questions raised by differing theoretical perspectives. In one study a mathematics department was viewed as a complex system and analysed accordingly. In the other activity theory was used to describe and analyse features of the departments involved. In both cases the departments involved were considered to be systems and it was the learning of the system rather than of individuals that was of interest. The affordances and limitations of the analytical perspectives are discussed.

In this paper, mathematics departments are seen as identifiable systems, operating with a purpose that distinguishes them from other groups of people within their respective schools. Although mathematics teachers may have other roles, such as being form tutors, teaching other subjects, or undertaking management responsibilities outside the teaching of mathematics, they belong to the mathematics department with respect to their work of teaching the subject. Departments concerned with teaching different subjects may operate in similar ways for many purposes, such as putting school policies into practice, responding to timetable designs, preparing reports, reporting assessment information and so on, but might also be distinguishable through characteristic epistemic cultures (Knorr-Cetina 1999), in that the concerns of mathematics departments might have some things in common with other groups of people concerned with mathematics just as art departments might have some things in common with other groups of people concerned with art. For the purposes of the studies reported in this paper, it was assumed that they would be distinctive in ways which might be epistemic. We also assume that they would be distinctive in ways which relate to current trends in school mathematics teaching in England such as the possible shortage of mathematics teachers (so that 25% of classes at this level have to be taught by people not qualified in the subject); high turnover of mathematics teachers; pressure for results as schools are compared using test results in core subjects; the high political focus on mathematics; and the inherent difficulties of teaching and learning the subject. The departments on which this paper is based were also distinctive in being subjects of research.

Complexity theory and activity theory offer two different ways of describing and analysing systems. In this paper we briefly describe salient features of each, outline their respective use in two studies of mathematics departments, and compare what each offers as a theoretical perspective through which to analyse school mathematics departments.

Davis and Simmt (2003) explained how complexity theory has developed in recognition of the fact that some systems cannot be understood using conventional analytic tools. That is, the behaviour of some systems cannot be predicted by analysing the actions of individual elements of the system. This is not simply a problem related to the difficulty of analysing large numbers of such interactions but to qualitative differences between systems that are complicated by virtue of the numbers of interactions, and systems that are complex. Complex systems typically comprise living agents who are autonomous, at least to some extent, and are characterised by features that are emergent in that they arise from the interactions of agents but cannot be directly attributed to particular agents (Davis & Simmt, 2003).

Complex systems are also adaptive in that their response to a given stimulus is dependent not only on the stimulus but on the history of the system. Complex systems thus embody their histories as they adapt to their environment and hence can be described as learning. Applied to human systems, learning can be seen as an emergent feature of the collective, and knowledge as residing with the collective rather than with individuals (Davis & Simmt, 2003). This is not to deny the existence of individual learning because individuals too can be described as complex systems nested within others. Indeed, Davis and Simmt (2003) illustrated the nestedness of complex systems by referring to the relationships between cells, organs, individuals, and society, all of which learn in the sense of adapting to their environment.

Davis and colleagues (e.g., Davis, 2004; Davis & Simmt, 2003; Davis & Sumara, 2005) have described educational settings in terms of complexity theory and have described five necessary but not sufficient conditions for emergence to occur. These are: *Diversity* among agents (typically students in a class) which allows for novel responses; *Redundancy* in the sense that agents have sufficient in common to allow meaningful interaction and to compensate for each other's weaknesses; *Enabling constraints* that balance order and focus in the collective's activity with the expression of its diversity; *Decentralised control* that recognises that outcomes, including the emergence of complexity, can not be predicted but instead emerge from the collective activities of agents; and *Neighbour interactions* between ideas rather than simply between agents.

Although these conditions have proved useful in describing educational settings (e.g., Sinclair, 2004) there is necessarily intentionality on the part of a teacher whose conception of teaching is essentially one of engineering an environment to include these conditions. (Towers & Davis, 2002). Davis (2005) attempts to deal with the dual role of the teacher as one of many agents in a classroom in which purpose is an emergent feature, and the teacher's intentionality by likening the teacher to the consciousness of the collective whose role is to direct and focus attention and to choose among possible interpretations and actions open to the collective. Although helpful, this falls short of recognising the capacity for intentionality characteristic of all agents in a collective of human beings. Unlike other living agents that comprise complex systems, humans are not obliged to act according to rules (although their may be powerful forces that encourage them to do so) and hence any agent in a human system has the capacity to disrupt or alter the system through the exercise of choice (Kurtz & Snowden, 2003). A skilled teacher is able to notice emerging patterns, intervene to stabilise those that are helpful (in terms of his/her intentions) and destabilise those that are not, and to structure the environment by *seeding* it or creating *attractors* around which patterns of interaction emerge, so that desired purposes and outcomes are likely to emerge (Kurtz & Snowden, 2003).

Activity theory focuses analysis on structured features of a department's work and the ways in which they interrelate. Activity consists of a group of people engaged in activity (the *subject*: in this case the teachers, student-teachers and classroom assistants), the direction of their work (the *object* or motive: in this case the mathematical learning of the target students), the *goal-directed actions* which are needed to achieve the object, and the *operations*, or routines, which keep the system working fluently (Leontiev, 1974). These operations can be subcategorised as *rules*, *community* characteristics, and *division of labour*. All these features are in balance, so that if one changes, other changes will take place to adjust the whole system. The object might change as a result of activity, and the activity might change as the object changes. This inherent instability is recognition of the nature of human agency within a system, and that the object is dependent on how it is understood by the people concerned. Despite this instability, patterns of behaviour within the system are often fluent, well-practised, and by-and-large replicate patterns of school subject departments in general.

The role of *mediating tools* in learning is multi-layered: Teaching and learning in classrooms can be seen as a knowledge-creating process of interaction between teacher, learner, and mediating artefacts. In mathematics, these include concrete tools such as boardpens, textbooks and computers and also less transparent tools such as language, symbols, analogies, examples.

Study A

Study A, Development of a Mathematics Departmental Culture (DMDC), concerned a department which had recently undergone significant staff changes. There was a new Head of Department, (HoD), a new teacher with responsibility for Key Stage 3 (lower secondary) and essentially ‘third in department’, and two newly qualified teachers. The school had specialist mathematics status, and the extra funding which derived from this meant that the HoD had been appointed at Assistant Head Teacher level with a brief which included teacher development, community engagement, and dissemination of good practice. The existing team comprised six teachers, including two other Assistant Head Teachers who taught 50% of a full load, and two heads of year. One of the assistant heads and one of the heads of year were not mathematics specialists but had trained in physical education and music respectively, with the latter dividing her teaching equally between mathematics and music. Both had taught mathematics for many years and the other teachers all had strong backgrounds in mathematics. Three of the team were studying, or had recently pursued academic professional development courses at a nearby university. The study was conducted in the first term of the school year and aimed to describe how the department developed as an entity. Particular foci were the development of shared beliefs and the ways in which individuals adapted to one another and influenced the department as a whole. Data comprised: individual interviews with each of the 10 department members at the beginning and end of the term; additional interviews with the HoD, the new third in department, a newly qualified teacher, and a teacher who had been at the school for a number of years; and audio-tapes and observations of departmental meetings.

Complexity theory was considered an appropriate theoretical tool in this context because the new HoD’s brief included change, or learning, at the departmental level. In addition, although an established department may have norms of practice and interaction that have been implicitly or explicitly agreed to and hence not be complex, the influx of new staff would necessarily require the renegotiation of roles, relationships, procedures, and patterns of interaction such that the outcomes would be unpredictable. Emergent phenomena included: an increasingly shared understanding of the meaning and importance of mathematical thinking in improving students’ attainment; consensus around the idea of providing access to higher levels of attainment for all students; a long term view of improving attainment; and a shared sense that the department was supportive. Although it is possible to identify contributions made to each of these by individuals their emergence is not entirely explicable in terms of direct causal links. Rather, they appeared to arise from interactions among the teachers in a form that was not precisely represented by any individual contribution.

The particular focus in this paper is the use of complexity theory to retrospectively analyse the HoD's attempts to influence mathematics teaching practices in the department. Since emergent phenomena can be perceived but not predicted (Kurtz & Snowden, 2003) such retrospectivity would have been necessary even if she had been consciously attempting to create the conditions for complexity (Davis & Simmt, 2003). The extent to which each of the five conditions for complexity were present in the department and the purposeful use and management of attractors by the HoD are described below.

The HoD had clear purposes in mind which she articulated throughout the term in the context of interviews, staff meetings, and in informal contexts. These related to enhancing students' opportunities to achieve, and focussing on students' thinking and how that could be moved forward in such a way that they achieved deep understanding of mathematical structures. She saw the two as related in that deep thinking and understanding would contribute to long term gains in achievement. She also likened the department's learning to that of students and compared the way she would like the department to operate to the way in which she wanted classes to operate. That is, characterised by deep, independent thinking, sharing of perspectives, and both individual and collective construction of understanding.

The ingredients for complex emergence (e.g., Davis & Simmt, 2003) appear to have been present in the department partly as a result of the HoD's choices and partly as a result of outside influences upon it. The diversity of views and approaches to mathematics teaching represented by the ten teachers was mentioned by several teachers when prompted to describe the department's strengths. The HoD also acknowledged the diversity represented by the teachers when she described the professional learning needs of the department as follows:

> … it's a question of people really building up their own areas of expertise and following those rather than one size fits all. In terms of one size fits all that's more of our working together rather than using people from outside. Take for instance, how to introduce algebra, I think we've got the skills between us to work together on that, and where it's a question of people following their own levels of expertise and areas of expertise, there are people that they need to work with perhaps on a national level …

Much of the redundancy evident was a consequence of the teachers' familiarity with the English National Curriculum, examination procedures, and usual school organisational practices that included setting on the basis of prior attainment. The overriding importance of ensuring that the school's examination results were satisfactory was taken as a given and enhanced opportunity was understood in terms of making higher grades accessible to all students. The strong mathematics background of eight of the teachers, and extensive experience of mathematics teaching of all ten, enabled all to participate in conversations of a mathematical nature. Interestingly, the externally imposed constraints of curriculum and examinations not only contributed to redundancy but also appeared, by virtue of their familiarity, to act as enabling constraints for some teachers. It seemed that the system requirements had been internalised by all of the experienced teachers to such an extent that they felt some degree of freedom to experiment with teaching approaches. The HoD expressed a similar view of school level policies, explaining that, "We really do have quite a lot of freedom, that's the sort of feeling I have".

Enabling constraints were also provided by the HoD as she worked to encourage conversations about students' thinking. These included asking teachers to bring examples of students' books to a departmental meeting so that the ways of providing feedback could be discussed. Initially only the HoD herself had examples to share but at a subsequent meeting a few other teachers also brought examples. On another occasion teachers were asked to bring examples of how they had incorporated the idea of equivalence into their mathematics teaching of any topic with any class and the request included a brainstorm of opportunities in which the idea might arise. Most teachers did report examples of highlighting equivalence in their teaching. The purpose of enabling constraints is to balance order and the expression of diversity (Davis & Simmt, 2003) but, since the unit of analysis is the system as a whole, complexity theory does not offer an explanation of why the same constraints appear to be enabling of some individuals but not others. Other perspectives that take account of social relationships might be better able to do this. From Kurtz and Snowden's (2003) perspective, enabling constraints can be thought of as attractors which establish a degree of order around them. The unpredictability of the impact or effectiveness of attractors, or even whether an influence on a system acts as an attractor at all, is inherent in the nature of complex systems (Kurtz & Snowden, 2003).

Other attractors included the HoD's enthusiasm for mathematics and for teaching, her constant references to students' thinking and the need to move it forward, and the fact that most of the teachers in the department had desk space in a team room. The HoD's references to thinking included an A4 poster she created with the slogan, "Learning to Think, Thinking to Learn" that was displayed in several of the mathematics classrooms and the team room, and was referred to by several teachers when they were asked about the department's ethos. The energy that the HoD devoted to teaching was evident to her colleagues who saw her as having high standards.

The team room's function as an attractor was due to its role in facilitating neighbour interactions. The HoD, the two newly qualified teachers, the new 'second in charge', and two teachers who had been in the school for a number of years all spent most of their non-teaching time in that space and informally shared their practice. The usefulness of these conversations was described by the HoD as follows:

> Sometimes we're working and talking at the same time, there's lots of it, and somebody else comes in and they join in. People seem to be much more ready for that than if you were to convene another formal meeting because they don't feel they have to be there, they're drawn in by interest, and then they make a contribution and they don't have to do exclusively that, they might be sorting through a few tests while contributing to the conversation …

Others who did not work in the team room because they had office space elsewhere (i.e. the Assistant Heads and one head of year) or who chose to work in their classrooms still made regular visits to the room to collect and return resources stored there or to seek out advice. The HoD recognised the value of such interaction and, in Kurtz and Snowden's (2003) terms, acted to stabilise this emergent pattern by proactively ensuring that she regularly visited the teachers who primarily worked elsewhere.

The department was necessarily constrained by school and system requirements but in other ways the teachers were autonomous and hence control was largely decentralised. The HoD was aware of the need to provide a safe environment in which people could take risks as they tried to change their practice. To this end she avoided directly observing her colleagues' teaching but instead monitored practice principally through conversations with them and also by listening to classes as she walked through the corridors. In her words:

> I'm not keen on doing things which I think leave the person feeling insecure and on the hop. What I want to do is … get somebody to take risks and work outside their comfort zone. They're much less likely to do that if they think you're about to barge in any second and I think what you need is just somebody to say well okay, the students are here, we want them to be here and we need to take risks to get them from here to here and if they think that the game is that any second you're about to walk in, I think for most us that's very risky, … I probably do a bit more from the corridor than people realise I do.

Study B

Study B is a three-year funded ethnographic study designed to tell the story of three mathematics departments as they set about making significant changes to the ways in which they teach mathematics to low-attaining students. Two of the schools serve inner-city areas of social deprivation, one of them highly multicultural, the other predominantly white working class. The third school serves a wide rural area. In England it is usual to teach students in different groups according to prior attainment, and the study focuses on those who would end up in 'low' groups under this system. Such groups typically include students from the most disadvantaged socio-economic groups, even in comparatively well-off areas. A range of data has been collected: teacher interviews, lesson observations and videos, notes and audio-recordings from department meetings, schemes of work, lesson ideas, student interviews, test scripts, national test scores, students' work, and background data about past achievements and school statistical predictions. The units of analysis are (i) a sample of students from one cohort as it passes through the first three years of secondary education, and (ii) the department as it organises their mathematical experiences. The academic task is to connect the departments' activity to the achievement of the students, to identify factors which contribute to success or otherwise; and to tell plausible stories about how the departments operated.

The capacity of activity theory to describe the interplay between stable practices and instability in the departments made it a suitable frame for our analysis. For this paper we are interested in the structures which enable the department to pursue its purpose, in particular the tools, including teaching tools and also department tools such as meeting agendas, resource banks, emails and memos that enable the activity to take place. It seems, in our analysis, that there are other features which are not usually described as artefacts but which also have this role in departments: individual knowledge is one of these, and the nature of meetings is another. One of the outcomes of this study is more understanding about the nature of 'tools' which mediate knowledge within mathematics departments.

During the analysis we noticed that the object of the system was also the object of individual classrooms, and that these too could be seem as activity systems, albeit with different subjects and communities, so the third generation activity theory developed by Engeström (1998) seemed an appropriate way to continue. In fact, Engström (1998) used this to lay out the behaviour of a school mathematics department undergoing deliberate change, with the same distinction between departmental activity and classroom activity.

In this paper, we refer to semi-structured interviews with teachers in the three schools who were teaching year 7, the entry cohort to the study. These interviews were undertaken at the start of the study, after decisions had been made about how year 7 was to be taught, and again towards the end of the first year. Interview data is, of course, highly subjective but is appropriate for this analysis because activity systems depend on human consciousness and agency and hence affective self-report is informative. Other data will inform us about enacted intentions and learners' experience, but the analysis of these is beyond the scope of this paper.

Content identification was used to confirm that the categories associated with activity theory would enable us to sort and categorise what was said for each separate interview, and then enable further comparisons, such as between teachers, between schools, and between interviews with individual teachers, to be made. We could thus construct shared understandings and contradictions within schools, similarities and differences between the three schools, and changes during the first year.

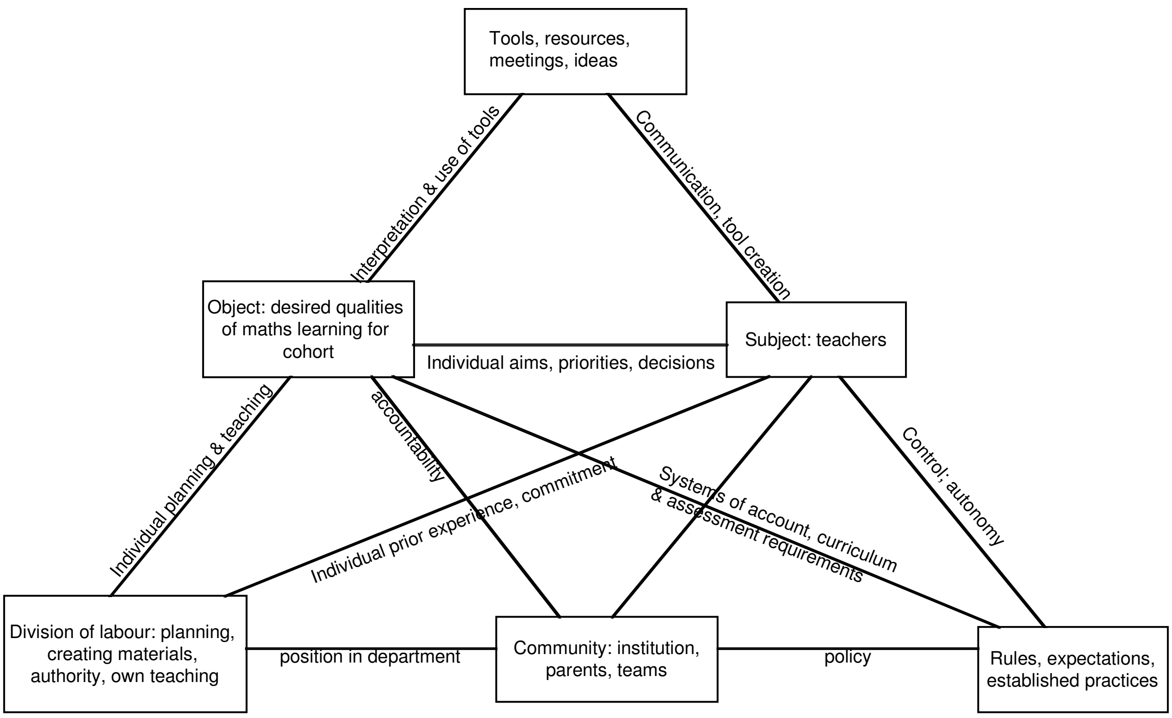
The process of analysis threw up many interesting observations, before such comparisons were carried out. Having decided that activity theory was the most appropriate framework, what followed was an exercise in: fitting the data to the structure, and seeing what did not fit; seeing whether the structure could be interpreted to accommodate the data; and questioning the structure and the data. These processes embody the way in which structures are used as tools to mediate meanings in data, and can symbiotically imbue data with meaning. The analytical questions are: 'What can this data tell me if I look at it with this perspective?' and 'What do I learn about this perspective from this data?' The following examples are illustrative:

Many teachers talked of contributing ideas to the department resource bank in their school. This action seems to describe a division of labour. However, by contributing an idea to the bank, they were also contributing *their ways of seeing the teaching of mathematics*, either through the bank or through discussions about their suggestions. Thus, their knowledge was more than something they did individually, but became available to be used by others – a potential pedagogical tool. In this sense, individuals' knowledge can be seen as a mediating tool within department teams to learn more about pedagogy. Further, department meetings could be described as a feature of the way the community operates, or as part of the rule-structure of the department, but the discussions which take place in them can be seen as mediating devices for pedagogical learning. When interviewees mentioned department meetings it was always in the latter sense, rather than in the sense of a departmental structure or rules of behaviour. This description of individual knowledge acting as a tool within a department, to be taken up and used by others, seems more useful in this context than to see it as merely part of more generally distributed knowledge.

There were interesting differences between what people said was supposed to happen and what actually happened. The most common was that they were all supposed to contribute ideas, but in the schools where this meant 'put some lesson plans into the file' most claimed not to have done that. Thus 'division of labour' was that some did and some did not, whereas 'rules' included the expectation that all would do so. We expanded 'rules' to include ‘expectations’ so that ‘division of labour’ could be left to describe what people said actually happened.

For Engeström (1998), the interesting thing about systems is how they learn, where learning is understood as the constant flux between internal inconsistencies and their resolution. Asked about priorities for year 7, the teachers in one of the schools began the year with the shared aim, articulated by all teachers, that students should ‘enjoy’ mathematics. By the end of the year many teachers were saying that they were concerned about students’ basic knowledge and that ‘skills’ were one of their priorities. This was not a stated aim through departmental communication channels, but had emerged from the grounded experience of the teachers. The object, in Leontiev’s terms, had been transformed through activity. For these teachers, their classroom aim incorporated ‘basic skills’ but the department rhetoric was still about ‘enjoyment’ and not about curriculum coverage. This could be seen as a rupture between the department and individual classrooms, or could be seen as transformation of the object of the department. Resolution had to involve restructuring of a tool, the scheme of work, but also negotiation of priorities and individuals’ ways of seeing their work.

A more dramatic finding was in the interpretation different teachers made when they imagined they were talking about the same thing. In one school, some teachers talked about open-ended tasks and investigating mathematics while the HoD talked about learning mathematical structures, as if they were all aiming at that. Meanwhile, in formal and informal interactions, everyone appeared to believe they were talking about the same thing apart from a few teachers who were known to be adhering to a transmission form of teaching. The latter difference was overt and seen as a training need; the former was not recognised by anyone except the researchers. Here again, there are queries about interpretation of the shared object. For some teachers this was shown in the very different uses they make of ‘the same’ artefacts, that is the meanings with which they were imbued by individual teachers in classrooms were different, and knowledge of pedagogy was not unambiguously mediated through the resources. Some teachers did not use the resource bank at all: there was no shared object, and no common tools, although the teachers were



actors in the same system because they taught the target groups, or because they were in our research project!

Figure 1: The work of the mathematics departments seen from an activity theoretic perspective (after Engestrom, 1998)

The triangle in Figure 1 gives more detail about how the interview contents were interpreted and structured in our analysis. In this diagram we have been able to represent all aspects of department activity as described by the teachers, except, as we said above, values, and reasons for individualisation of interpretations, objects and actions. We were able to describe systemic influences on relationships between the points on the triangle. There were highly individual differences in dealing with external requirements, such as accountability. HoDs in two schools gave guidance which was much less prescriptive than several teachers chose to adopt. For this reason 'accountability' does not appear under 'rules' or 'community' but edges more towards individual interpretation of the object.

Activity theory has helped us to make sense of most features of departmental activity, with respect to the target students, and has also enabled us to connect classrooms with departments as systems which *may* have common purpose. From these linkages, and attempts at linkage, we found some conflicting aspects for which resolution was likely to change the system. This analysis did not, however, enable us to make sense of different teachers' interpretations of goals and artefacts in their action, and how these related to the department's work. Nor did it enable us to deal with ruptures which depended on interpretations of the object (what it means for the target group to learn more mathematics) rather than changes in the stated object itself. Indeed, it did not allow us to structure interpretations and value systems into our analysis – but it did reveal them, and showed that these differences were conflicting and that there were splits and potential splits, both known about and unknown.

Comparing the affordances of the different theoretical perspectives

The overarching question in choosing between complexity theory and activity theory is, 'Is this department a complex system (characterised by emergence and adaptation) or is it more like an activity system, in that it is totally structured?' The choice necessarily influences what is looked for and noticed. In the four departments considered in these studies, there were aspects of their functions that were known, predictable, and governed by agreed procedures and allocated responsibilities. In Study A these aspects included the compliance with examination entry procedures and setting, but the aim of improving students' attainment was a shared goal in relation to which each teacher acted autonomously albeit influenced by their interactions with one another and particularly by the intentional interventions of the HoD. In Study B important aspects of the departments' efforts to achieve their aim of raising attainment for a particular group of students were much more structured. This difference can be attributed to the facts that the aim in this case is more tightly defined (i.e. it was a condition of involvement in the research and was subject to timelines and measurement), and that the aim was not necessarily in tune with the aims of each small grouping within the system. For this reason it needed to be managed centrally with questions like, 'Who will take responsibility for this necessary task or role?'

(division of labour) and, ‘What common tools do we need to carry this out?’ It thus seems that choices made by leaders in relation to bringing about change, particularly whether they attempt to facilitate the emergence of the desired aim or seek to devise and impose systems that will further the aim, are highly relevant to whether the system is best thought of as complex system or as an activity system.

A further difference between the two approaches is how each perspective deals with change. Both claim to show how systems might continually change and learn. Activity theory, however, seems to see change as structural disruption, in that systems necessarily contain, within their ways of functioning, relationships which might break down, or might be in conflict with other relationships. Thus change is manifested as a crisis which requires reorientation of parts of the system, renegotiation of roles and rules; introduction of new mediating tools and meanings; and redefinition of objects. Activity theory predicts and models the reorganisation which precedes and follows a change in heads of department, and also shows up the potential problems arising from a lack of shared objectives, or from contradictory interpretations of objectives. Complexity theory embraces change as a necessary characteristic of systems, recognises that change to one part of a system trigger adjustments throughout, and sees ‘adjusting’ as part of the overall dynamic functioning of the system. Complexity theory is therefore better at describing fluid systems in which related members take a large number of autonomous decisions (decentralised control) members work in parallel and might influence each other through neighbourhood. We also found that activity theory allowed us to incorporate some institutional requirements directly as rules, which may have been alien to the department, whereas incorporating institutional requirements in study A as aspects of complexity did not show whether they had an alien and contradictory quality.

Just as the Study A department included aspects that were highly structured, aspects of the Study B departments’ functions, for example the teaching of mathematics in classrooms, were less structured and arguably less amenable to analysis using activity theory. It was for the specific task of the departments’ teaching of one cohort that activity theory, and the attempt to describe the activity as a structure was useful in showing up conflicts, gaps and differences in interpretation. Complexity theory tells us about diversity and unpredictability which are inherent in human systems, whereas activity theory offers a tool to analyse activities that at least for a time seem structured and predictable. Neither is capable of adequately dealing with the role of individual differences of action and interpretation within the system nor claims to be.

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