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Assembly required: a microgenetic multiple case study of four students' assemblages when learning about force

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ABSTRACT

Some descriptions of learning represent the process as the development of organisations of elements. Various organisations have been proposed, for example, schemata and conceptual structures. Such representations assume that mental entities, such as concepts, are sufficiently stable and differentiated to be treated as units. We discuss these assumptions and propose a new term, assemblages, to refer to a person's activation of two or more conceptual resources in a context. Methodological challenges have resulted in a lack of research that examines how assemblages are formed. This study presents data from a microgenetic, multiple case study of four 16-17-year-old students. The participants were interviewed weekly, using various probes related to forces and motion over six months. We focus on two aspects of the assembly process in our analysis. First, we report data that indicate that participants perceived the units they assembled differently from expert conceptualisations and reflect on the stability of their assemblages. Second, we discuss how participants' expectations about the coherence of knowledge impact their assembly. We propose that future research investigates the stability and boundaries of conceptual resources and suggest teachers and researchers are cautious in assuming that data indicate a conceptual resource is stable or unitary.

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Introduction

An aspect of educational research is the construction of models of learners' thinking with the intention of informing teaching (Taber, 2013). These models are intended to reflect, as faithfully as possible, students' learning processes. All models are limited and learning models are only ever partial representations of the complexity of cognition. In science education research, a common representation of learning is to model changes to organisations of mental entities, for example, changes in collections of concepts, conceptions, ideas and so on, such as cognitive structures or schema (Ausubel, 2000; diSessa, 1993;

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Sherin, 2021). Whilst such representations are pragmatically useful, they assume that the elements being organised can be treated as units, that is, the elements can be meaningfully separated from each other and are sufficiently stable to be represented as prevailing constructs. In the first section of this article, we consider the artefacts and affordances introduced by representing learning as a process of assembling structures from elements. As we describe below, models of organisations of elements, such as conceptual structure, make assumptions about the nature and stability of the elements. Hence, we will use a novel term, assemblages, a person's activation of two or more conceptual resources in a context. The idea of assemblage derives in part from the writings of French philosophers Deleuze and Guattari (2013) and has been given greater specificity by, for example, Nail (2017). We use assembly to refer to the process of developing an assemblage. In the second section, we report the assemblages of four students in the context of force, which we conceptualise as a multiple case study. The participants were interviewed at a relatively high frequency (weekly) over an extended period of time (six months), using the microgenetic approach (Siegler & Crowley, 1991). Finally, we reflect on the value and limitations of learning represented as assembly.

Theoretical models: representations of the elements of assemblages

Before considering assemblages, it makes sense to examine what is being assembled and the distinctness and stability of those elements. We consider two models of assembled units, the concept and the p-prim. First, one of the more commonly used representations of mental entities, the concept, refers to categories or classes that organise information (Medin & Rips, 2005; Murphy, 2002; Sloutsky & Deng, 2019). For example, for one individual, the concept of plant might organise their beliefs about living things that photosynthesise, for example, knowledge that plants require sunlight to photosynthesise, and that chlorophyll is a green pigment. Concepts, in this understanding, are not atomic entities but have internal structure (Gelman, 2003; Lakoff, 1987; Levering & Kurtz, 2019). As well as being compound entities, concepts have different degrees of stability. Concepts are brought mind to make sense of some context, in a (conscious or tacit) process referred to as activation (Becker et al., 2024; Hammer et al., 2005). The stability of a concept can be assessed by how often the concept is activated, in the same form, in similar contexts (we discuss the limitation of this assumption below). Several relatively unstable types of concepts have been proposed. Piaget (1929, p. 10) reported children might engage in 'romancing', responding to an interview probe with an answer to which they have little conviction. Barsalou (1983, 1987, 2005) suggested people use 'ad hoc' concepts, categories constructed pragmatically, in the moment, to make sense of a context. Carston (2002, p. 322) refers to concepts constructed 'on-line' or 'on the fly' to meet a momentary communication need. Whilst evidence of instability has led some researchers to reject the notion of stable concepts per se (Barsalou, 1987; Smith, 2005), we assume that concepts have a probabilistic structure, with some elements being more stable than others, and that some elements of people's concepts show considerable stability over time and contexts (Frankenberg et al., 2022; Mazzone & Lalumera, 2010). Their compound nature and the variable stability of their elements suggest that caution is needed when modelling concepts as unitary, stable entities that make up assemblages.

Second, a widely discussed model of assembly in the context of science education, diSessa and colleagues' 'knowledge in pieces' model (diSessa, 1993, 2002; diSessa & Sherin, 1998), presents a fine-grained representation of change. The organised elements in the 'knowledge in pieces' model include phenomenological primitives (p-prims) which are described as intuitive representations of mechanism which are both 'atomic' (diSessa, 1993, p. 112) but also ' … typically involving configurations of only a few parts' (diSessa, 1993, p. 111). By referring to their resistance to change, diSessa implies that p-prims are relatively stable. As described, the relatively stable and unitary character of p-prims makes them comparatively well-defined assemblage elements.

Theoretical models: representations of assemblages

Several terms have been used to refer to organisations of mental entities, including schemata (Bartlett, 1932), conceptual structures (Novak, 1966), cognitive structures (Shavelson, 1972), and coordination classes (diSessa, 2002). For example, in the 'knowledge in pieces' model, p-prims are elements of coordination classes, systems that allow the consistent activation of conceptual resources across contexts and over time (diSessa, 2002). Disciplinary experts are reported to consistently apply assemblages of conceptual resources linked in well-defined relationships (diSessa, 2002; Taber, 2009; Wing et al., 2022). By contrast, novices (and experts in some conditions) may construct short-lived assemblages to make sense of unfamiliar situations (Barsalou, 1983; Piaget, 1929; Taber, 1995). The formation of assemblages may be guided by an individual's interpretation of the expected behaviours in a context (Hammer et al., 2005). For example, in the context of solving physics problems, whether a quantitative or qualitative solution is expected. An aspect of this framing are epistemological assumptions, beliefs about the nature of knowledge and learning, that might guide the assembly of resources.

Descriptions of learning propose that the repeated activation of conceptual resources can lead to mental representations with considerable stability, for example, memories that persist over many decades (Baddeley, 1997; Frankenberg et al., 2022; Shavelson, 1972). By contrast, people also make use of relatively temporary assemblages, which persist for seconds or minutes (Parnafes, 2012; Sabella & Redish, 2007; Wittmann, 2002), for example, 'ad hoc categories' (Barsalou, 1983), and 'mental flotsam and jetsam' (Taber, 1995, p. 95). Defining the stability of an assemblage is challenging, and few models of stability exist in the context of science education research.

The ability to consistently develop assemblages that match scientific models across contexts is a valuable ability and a marker of expertise (diSessa, 2002; Reif, 2008; Taber, 2009). However, possessing stable expert assemblages is not unequivocally beneficial. Research into concept learning via supervised categorisation (in which a learner assigns an image to a category and receives feedback) suggests that as learners become better at categorising cases, their ability to form novel distinctions can be reduced (Hoffman & Rehder, 2010). For example, as learners get better at categorising first pictures of cats and dogs, then images of possums and racoons, they may get worse at distinguishing cats and possums. Experts develop automated processing which enables rapid responses but can diminish their ability to respond flexibly in novel situations, the Einstellung effect (Bilalić et al., 2008). Flexibility in the assembly of conceptual resources allows variation in responses which can support the generation of solutions to novel problems (Taber, 1995). Indeed, high variability in conceptual activation has been reported to precede learning (Adolph et al., 2008; Siegler & Chen, 1998). The benefits and hinderances of flexibility in assembly suggest there is an optimum level of stability of assemblages that affords sufficient consistency of activation across contexts and over time, but with enough instability to allow adaptation to novel contexts.

Issues for research into assemblages

Cognition might be thought of as a continuous stream without 'natural' divisions (Spivey & Cargill, 2007). Nonetheless, constructs like the concept and the p-prim can be useful when describing patterns in people's responses because they indicate underlying stabilities in application. However, the constructs can become reified, implying greater stability of application and discreteness than is the case. Researchers might well report their assumptions about the stability and boundaries of proposed elements. In this paper, we will refer to the elements of assemblages as conceptual resources (diSessa, 1993; Hammer, 2000; Taber, 2008). Whilst there is widespread agreement that learners' develop assemblages of elements, the properties of assemblages are not well understood (Sherin et al., 2012). In our discussion of the data, we present evidence of the stability and boundaries of the conceptual resources and assemblages described.

Discussions of assemblages often lack statements about the stability of the entities being discussed. This omission may arise due to two methodological challenges. First, perhaps due to their onerousness for participants and researchers, few studies have examined conceptual change with sufficiently high sampling frequencies and over extended time periods to be able to represent resources of differing stabilities (Brock & Taber, 2017). Second, researchers only have access to what an individual 'brings to mind' in a particular context. The type, context and sequencing of research probes will influence the conceptual resources activated and representations of the stability of assemblages (Sherin et al., 2012). The compound nature of assemblages can be hard to represent in research tools, such as interviews, where networks of associations are implied from sequential reports (Sherin, 2013).

Despite these challenges, several models of assemblage stability have been proposed. Georghiades (2000, p. 124) defined 'durability' as how long a conception 'remains in effect' but did not discuss the meaning of remaining in effect. Potvin and Cyr (2017) used the term prevalence to refer to a shift in the likelihood of activation of one or more conceptual resources and refer to the durability of change, but do not explicate the concept in detail. We define the stability of an assemblage as related to the period over which two or more conceptual resources are activated with consistent relationships, in the same context. It is challenging to separate the stability of an assemblage from the stability of its component conceptual resources. We present evidence in our data of the stability of the conceptual resources we discuss. We acknowledge that it may be difficult, empirically, to distinguish between a stable assemblage and an unstable one that is repeatedly formed in the moment and rejected. Data on response times and self-reports of levels of confidence are potential empirical approaches to representing the level of commitment to a response. Our discussion of stability draws on utterances made in interviews in response to probes and, though there may be some correlation, our construct of stability is not assumed to directly reflect the stability of mental entities.

Currently, in science education research, few descriptions exist of the stability of assemblages, that is how collections of conceptual resources are activated across contexts and over time. diSessa and his collaborators (diSessa, 2014; diSessa & Sherin, 1998) reported data from microgenetic case studies describing patterns of conceptual change over time; Dykstra et al. (1992) examined how students' dynamics concepts differentiate; and Koponen and colleagues (Koponen, 2014; Koponen & Huttunen, 2013; Koponen & Kokkonen, 2014) presented systemic representations of how assemblages related to electrical circuits developed. Whilst previous studies have produced fine-grained analyses of the assembly process (e.g. Sherin et al., 2012), exisiting accounts lack representations of change produced by sampling at both relatively high frequencies to capture fine-grained aspects of change whilst also extending over a sufficient period to support claims of stability. Our research reports data from weekly sessions, split into two blocks and a final session, over a period of six months to capture short- and long-term change to participants' force assemblages. We ask: First, how stable are the force-related assemblages of four 16-17-year-old students over a period of six months? Second, how do the students' assemblages, constructed in one context, change when encountering the same stimulus multiple times?

Method

The focus on change in our research question suggested the use of a microgenetic approach (Siegler & Crowley, 1991), a method in which the frequency at which the target concept is sampled is chosen to be high compared to its assumed rate of change. Assemblages were assumed to be changeable over short timescales (minutes and hours) hence change was constructed both within and between interviews (Brock & Taber, 2017). Models of expertise suggest assemblages can take months or years to reach a stable state (Blown & Bryce, 2006; Shuell, 1990), hence the interviews, in blocks of weekly sessions, covered a period of approximately six months. Especially for novices, the activation of conceptual resources can be contextually sensitive, so students were interviewed using probes of conceptual resources in a number of contexts related to force and motion to investigate transfer (see Table 1), with some probes repeated a number of times, to analyse the stability of participants' assemblages

Table 1. Probes used in the sessions.

	Probes or context used
1	Force concept questions
2	Pendulum, forces on a car
3	Mass on a spring, forces on an astronaut
4	Loop-the-loop, forces on a swung ball
5	Ball in a bowl
Sessions 6–10 on concepts related to electrical circuits	
11	Ball thrown vertically
12	Bag in a braking car
13	Leaping from a crouched position
14	Weightlessness
15	Force concept questions, ball in bowl, pendulum, and mass on a spring
16	Forces on astronaut, ball in bowl
Sessions 17–21 on concepts related to electrical circuits	
22	Force concept questions, pendulum, ball in a bowl, mass on spring, forces on an astronaut

(Demastes et al., 1996; Tao & Gunstone, 1999). Probes were selected which required the activation of a similar set of conceptual resources to form different assemblages, for example, the question on the motion of a ball in a bowl (see Appendix 1) and a pendulum, prompt the activation of force, acceleration, and velocity conceptual resources.

The participants in the research were five 16-17-year-old students, taking an elective physics course at a state-funded secondary school (for 11-18-year-old students) in England. Students aged 16-17-years old were selected as they were likely to possess both stable and unstable assemblages. One student withdrew after five weeks, citing the pressure of studying for exams. Her data are not reported. The students are referred to by the pseudonyms, Ben, Charlie, Daniel and Edward. A purposeful sampling strategy of selecting extreme cases (Yin, 2009), through discussions with teachers, was used. Two students who were reported to develop coherent assemblages with ease (Ben and Edward) and two who were described as regularly struggling to relate concepts (Charlie and Daniel) were selected. Microgenetic researchers have justified small sample sizes by arguing that, when developing fine-grained representations, additional data collection sessions are more useful than larger sample sizes (Siegler, 2006; Sliwinski, 2011). The students and their parents gave informed consent to participation. The data reported are part of the first author's doctoral thesis (Brock, 2017).

Individual participants and author 1 met for 22 interviews of approximately 25 min, once a week, for 22 non-consecutive weeks, over approximately six months. The sessions were divided into two interspersed sets of sessions, focusing on forces and electricity. In this paper, we discuss data from the forces sessions. The interviews were semi-structured, allowing the researcher to clarify responses. Several types of probe were used including open-ended questions (Epstein, 2009) and questioning about a piece of apparatus, in an interviews-about-events like approach (White & Gunstone, 1992). Each interview was audio-recorded and transcribed.

Each participant is considered a distinct, bounded case, and we conceptualise the study as a multiple case study (Yin, 2009). Individuals' data are assumed to be situated in the contexts of their learning experiences, as is the norm in a case study (Flyvbjerg, 2006). Whilst the research interviews took place, the participants' normal lessons continued, and their responses are a product, we assume, of the research probes, lessons, and other learning activities (such as reading for interest) they experienced. Judgements of the extent to which the findings generalise to other learners in other contexts are left to the reader (Taber, 2000) and are a question for future research. Rather than reliability, when designing the study, we considered Guba's (1981) notion of dependability, which is supported by the use of multiple sources of data from different probes of the same concepts, and the establishment of a clear audit trail by reporting the data in detail. We believe readers' confidence in the validity of our findings is supported by presenting extended, verbatim quotations from the transcripts (Creswell & Miller, 2000).

Whilst the initial definition of the microgenetic approach required qualitative and quantitative analysis (Siegler & Crowley, 1991), subsequent studies in science education have used purely qualitative analysis approaches (diSessa, 2014, 2017; Parnafes & diSessa, 2013), a strategy we adopt here. The dataset was large (around 20 hours of recording and around 180,000 words of transcript). Given the size of the dataset, and that our aim was to report illustrative examples of stable and unstable assemblages rather than an exhaustive catalogue of cases, the first author performed the initial coding alone. Where utterances or sequences of utterances in the transcripts indicate participants engaging in assembly, a code was added, by the first author. For example, where a participant explains the motion of an object by linking net force to acceleration. Instances of stable assemblages (where the same resources were activated and related together in repeated encounters with a context) and unstable assemblages were noted. Whilst not involved in the coding, the first and second author provided a sense check on the coherence of the findings. Due to limited space, the findings section focuses on three students. First, descriptions of stable and unstable assemblages (Charlie and Ben), second on the development of assemblages (Ben and Edward).

Findings

The stability of assemblages

At one extreme, some assemblages constructed by the participants occurred on only one occasion. For example, in the first session, Ben was asked to predict the trajectory of an object dropped from an aircraft moving with constant horizontal velocity. His response linked his concepts of force and energy:

> I think the [horizontal] force acting on it [an object falling from an aircraft] would be much stronger than the force of gravity at first, so it would be practically vertical, well practically horizontal … But then, eventually, it would lose its kinetic energy gained from the push, and then the gravitational force would take over and it would just drop to the ground. (Ben, Session 1)

Ben's noncanonical assemblage in which force can take over from kinetic energy as a cause of motion is not seen elsewhere in his explanations and did not reoccur when he was asked the question again in the final session.

A second example of a short-lived assemblage occurred when Ben was asked to explain how an increase in mass would affect the time period of a simple pendulum. He first argued that when more weight is added, the tension in the string increases (a correct assumption), therefore the net force and acceleration increase, causing a shorter time period (an incorrect conclusion). When asked to use some apparatus to investigate the relationship between time period and mass, Ben was confronted with data that contradicted his prediction. He made sense of the discrepancy by suggesting that tension is unaffected by the change in weight:

> … because the force of tension is acting in the opposite direction to the force, in a different direction to the force of gravity, so I don't think the force of gravity affects the tension very much. (Ben, Session 2)

Ben had previously, in the case of a free-falling object (Session 1), argued correctly that acceleration due to the gravitational force is independent of mass, but he failed to reactivate that assemblage in this context. After a prompt from the interviewer, questioning the link between gravitational force and tension, Ben's third assemblage linked the pendulum's weight and its time period – when weight is increased, he argued, the time to move from maximum displacement to the equilibrium position is reduced, whilst the time to travel in the opposite direction is increased (a mistaken assumption). When Ben was asked to consider the symmetry of the situation, he rejected his proposed assemblage. In this case, Ben developed short-lived, ad hoc assemblages to make sense of the context, seemingly without a stable commitment to any one construction.

The data include instances in which Ben found two alternative assemblages to be equally plausible. When he was asked to explain the motion of a person travelling at constant velocity in a lift, he constructed two assemblages and expressed uncertainty over which to select:

> I would like to say that the reaction force is bigger [than the gravitational force]. Because he [the lift user] has to, at some point, [have] accelerated, because he's not stationary, but at the same time, he's not accelerating any more, and so they [the gravitational force and net force] should be equal, and so I am not sure whether the net force is greater or the same. (Ben, Session 4)

In subsequent comments, Ben developed both an assemblage in which motion required a net force and one, resembling the Newtonian model, in which constant velocity was linked to the absence of a net force.

In session 13, Ben was asked about the forces acting on a child jumping from a crouched position. When considering the instant the child leaves the ground, Ben struggled to reconcile his belief that a net force acts on the child with his misconception that, because of Newton's third law, the forces acting on the jumper must be equal and opposite at all times. This conflict led to the construction of two competing assemblages. Ben argued that the forces (the reaction force and the weight of the child) both did and did not occur simultaneously. He was aware of the existence of the two assemblages and reported both were plausible: 'I'm just not sure whether they occur instantly at the same time as each other, or whether there's a gap between them' (Ben, Session 13).

When asked why the net force on the jumper changes, Ben argued that 'she's putting less weight on the floorboards when she lifts her legs up' (Session 13). He proposed that the floorboards move down, reducing the weight acting on the surface, the jumper's weight therefore reduced because the area of contact with the floor decreased. As he continued to make sense of the context, he reported that the jumper 'herself puts some force into jumping' (Session 13). When prompted to explain in more detail, Ben proposed that:

> … when she crouches down, she's putting pressure, so the electrons at the bottom [of her foot] come closer to the electrons at the surface [of the floor], and so there will be not only a reaction force, but there will be a force causing the electrons in her feet to accelerate from the electrons in the floor. (Ben, Session 13)

Ben ultimately managed to develop an assemblage that linked net force with acceleration and velocity.

Whilst stable assemblages are an aspect of expertise, novice science learners may construct persistent assemblages which differ from those of experts. For example, in a discussion about the nature of forces, Charlie contradicted expert classification by suggesting that 'gravity' and 'weight' were distinct forces: ' … gravity and weight's always going to be down' (Session 13). This differentiation reappeared later in the same interview in the context of the pendulum: 'the gravity … And weight pulling it down [cause the acceleration]' (Charlie, Session 13). The activation of both 'gravity' and 'weight' as part of Charlie's assemblages displayed some stability, for example, in a force diagram he drew later in the session (Figure 1) in which he labels the downward force 'Gravity/ Weight'.

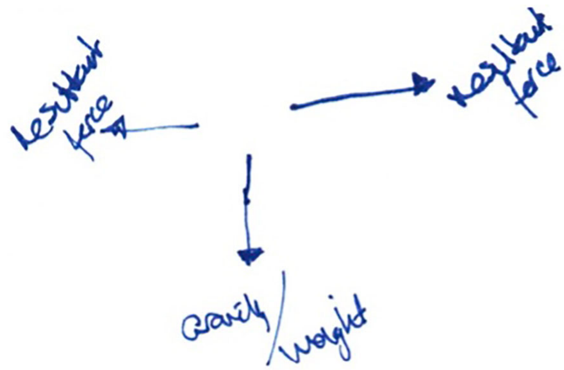

Figure 1. Charlie's representation of the forces on a pendulum (Session 13).

Charlie's conflation of weight and gravity was an element of his assemblages across several sessions over a period of around two months:

> … 'cos there's a heavier ball, and they both go same speed, 'cos one ball's lighter, the weight and gravity have a less effect. (Charlie, Session 15)

> … gravity always acts downwards … So that contributes along with its weight. (Charlie, Session 15)

> Because it's going down, and its weight and gravity would give a net force above zero. (Charlie, Session 15)

> … its mass would be down … There's gravity as well [pause] mass. (Charlie, Session 16)

In his final session, when directly questioned about the construct, Charlie indicated that he conceptualised weight and gravity as distinct concepts:

> C: So, there's still weight and gravity.
>
> I: Are those two separate things?
>
> C: Yeah, or yeah and …
>
> I: How are they separate?
>
> C: Gravity is the [pause] or the field strength. Acting on everything and then an object can have an individual weight.(Charlie, Session 22)

Charlie's responses highlight care is required when dividing reports of cognition into units.

Ben also showed evidence of a stable, non-canonical assemblage – the understanding that all forms of energy are associated with motion. This assemblage arose first in session thirteen, and was activated on three other occasions, including the final session, over a period of approximately two months.

> [Kinetic energy] causes movement in the sense that we say there are different kinds of energy, but in a way, they [forms of energy] are all, in some way, kinetic, because [in] light we have oscillating magnetic and electric fields … So it's kinetic. Heat, we have molecules moving so its kinetic … actually, all energy is kinetic. (Ben, Session 13)

> I go back to saying that all energies are manifestations of kinetic. (Ben, Session 14)

> … as we've said, all energy is a manifestation of kinetic energy. (Ben, Session 15)

> I think [the] foundation really is kinetic energy because it's an energy that I think really exists. (Ben, Session 16)

> I think even when we say something has so much heat energy, so much kinetic energy, as I've said before, I think they're all just kinetic energy. (Ben, Session 22)

Little attention has been given to the study of stable non-canonical assemblages like Charlie's 'weight'/'gravity' separation and Ben's understanding of energy. Both expert-like and alternative assemblages can be stable, leading to cases in which, like Ben, learners can be aware of coexisting, contradictory, canonical and non-canonical assemblages.

Non-canonical assemblages can seem to have explanatory power and be formed in preference of canonical assemblages. In the context of the oscillations of a spring, Ben struggled to form an expert assemblage and was conscious that his difficulties arose from a failure to assemble, rather than a lack of conceptual resources:

> I think my knowledge, in itself, is fine … But I think I'm quite weak in terms of when given a situation, thinking and considering every single thing that is happening … Because, at the moment, I'm not linking everything, so I might only notice two things … instead of the whole range. (Ben, Session 16).

Ben reported both an expectation of coherence ('I expect it to make sense in so much it has to be logical. There has to be a reason') and a tolerance for some incoherence (...'there will always be confusion and always be conflicting ideas'). Significantly, for Ben, incoherence was a spur to cognitive engagement:

> … not having coherence makes me then want to try to understand what makes it incoherent … I want to grow, and I want to look at different interpretations to try to fit it all together and in the trying to fit it all together I actually learn a lot, and a lot more than I would if I was just looking at the individual facts. (Ben, Session 1)

By contrast, Charlie reported an expectation that concepts would be challenging and placed an onus on the teacher to support his sensemaking: 'generally because it [physics] is a hard thing to take, so I'd expect it to be hard stuff to learn at first, so the teacher would have to thoroughly go through it all for me to learn it' (Session 1). He suggested that memorising facts was a significant aspect of learning physics, though acknowledged that practicing solving equations supported understanding. Edward similarly reported an expectation for content not to cohere: 'It is a very complicated universe so sometimes it doesn't always make sense' (Session 1) and reported, like Charlie, a reliance on external support to resolve incoherence: 'I would usually go and ask for help if I didn't fully understand what I had been taught' (Session 1). Edward and Charlie both see learning physics as likely to involve a feeling of incoherence that they expect to be resolved by their teachers. This assumption may explain why both students retained non-canonical assemblages (Edward's conflation of force and momentum (below), and Charlie's gravity-weight distinction) for extended periods.

The assembly process in the context of a ball in a bowl

The use of repeated probes allowed for the analysis of the assembly process in one context on several occasions. In the second section of the analysis, we compare Edward's and Ben's responses on three occasions when they were asked to explain the oscillations of a marble released from the side of a large concave bowl (a model solution is given in Appendix 2). The context was selected as it requires the assembly of multiple conceptual resources and the two participants chosen because Edward and Ben had the most extensive, and contrasting, responses to the probe of the participants. In his first response, Edward activated a limited number of resources, mainly related to the physical features of the situation:

> Isn't it something to do with the gradient [of the bowl]? And the gradient's like zero at the bottom, I think it's completely flat, it's zero at the bottom. It's like a large, it's a larger number at the side, so it [the ball] … moves down to the centre. (Edward, Session 5)

In his second explanation, Edward's focus moved away from physical features of the situation, and he activated his concepts of momentum and energy (though, see below, the two conceptions may be conflated):

> … as it gets higher up, the ball up the slope, it gains more gravitational potential energy … And so it would, it would, sort of, want to go back down towards the middle, in a sort of centripetal motion, so, and as it does momentum builds, so it goes back up the other slope. (Edward, Session 15)

In the final session, his assemblage involved resources related to force and momentum (see FIgure 2):

> E: … we draw a ball here then the forces acting on it would be parallel to the platform it's on, so the two forces would sort of both be going that way [draws ball in centre with two horizontal arrows, see Figure 2].
>
> I: What are the two forces there?
>
> E: In this case it'd be the forward momentum of the ball and the drag on it. (Edward, Session 22)

Edward's response in session 22 indicates the challenge of dividing reports of cognition into units. Whilst to an expert, the force concept is clearly differentiated from

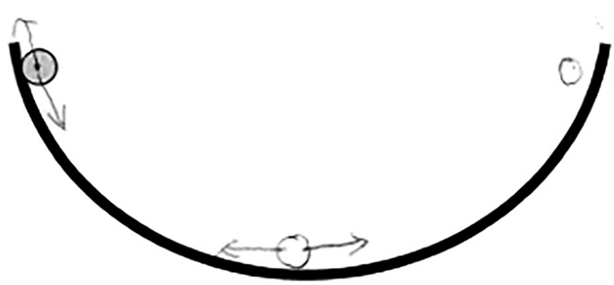

Figure 2. Edward's representation of the motion of a ball in a bowl (Session 22).

momentum, Edward appears to conflate the concepts, indicating blurred boundaries between his resources. For analytical purposes, it should not be assumed that Edward uses force and momentum as clearly differentiated units in assemblages. By contrast with Edward's original assemblage that invoked concrete features, Ben initially related abstract, symbolic concepts to explain the motion of the ball in the bowl:

> … because the force is gravitational field strength times by sine theta, I think, for the acceleration … as the angle becomes flatter the acceleration should be less (Ben, Session 5).

To explain the ball's instantaneous rest at maximum displacement, Ben linked zero velocity with zero net force, a common alternative conception, which he also activated in in the case of the jumper (see above):

> … because the velocity and force of the gravity will be equal, so it won't be going anywhere (Ben, Session 5).

In the context of the ball in the bowl, the net force arises from the resultant of gravitational and reaction force (see Appendix 2). A probe in Session 4, about a book resting on a surface, indicated reaction force is an element of Ben's conceptual repertoire, but he did not activate the resource in this context.

When Ben reencountered the ball-in-the-bowl, in session 15, his assemblage was enlarged through the addition of frictional force. Despite the increased extent of his assemblage, the friction concept was not deployed in an expert-like relationship. Ben argued that, when the ball was at the lowest point in the bowl, it travelled at constant velocity ' … because the friction and weight cancel' (Session 15). Ben again failed to activate the concept of reaction force and instead developed an assemblage that linked the ball's motion to the changing direction of the frictional force:

> Because it's slowing, its friction must, I would suppose, in well, it'd be as if the friction increased, and the friction is becoming more and more diagonal (Ben, Session 15)

In the final session, Ben's assemblage included an understanding of reaction force that changes direction depending on the ball's position with gravitational and frictional forces to produce an expert-like assemblage. A summary of Edward's and Ben's assembly processes are shown in Figure 3.

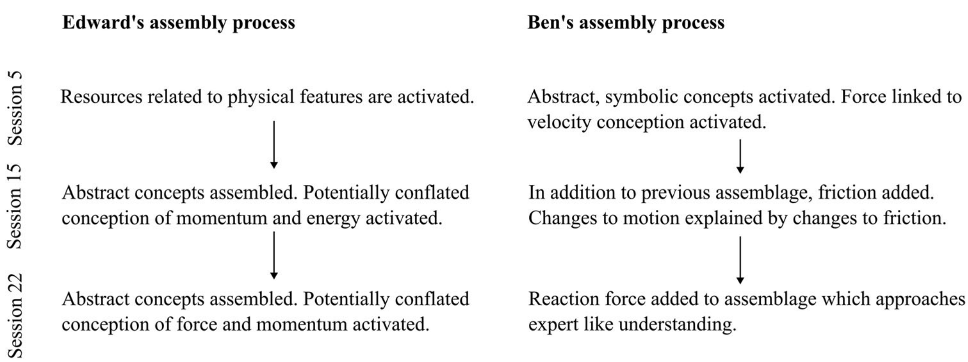

Figure 3. Edward's and Ben's assembly of resources in the context of the oscillations of a ball in a bowl.

Discussion: accounting for the stability of assemblages – an analogy with collage

The data suggest novices' responses can be represented as involving both stable and unstable assemblages. A goal of science teaching is to support students to develop stable, expert-like assemblages. When responding to stimuli, novices may form and discard relatively short-lived assemblages (Barsalou, 1983; Sloman, 2009). Such constructions might be thought of as trial assemblages in which relationships are proposed and assessed (Clement, 2013). Repeated activation of a set of conceptual resources together may lead to the development of stable assemblages. The assembly of conceptual resources, in response to a probe, is like the process of collage, an artistic technique in which different materials or objects are brought together to create an artwork. Just as a finished collage may appear coherent to one viewer but not to another, an assemblage of conceptual resources that is coherent to an expert might, to a novice, be composed of fragments that do not obviously relate. A focus on assembly, emphasises that the possession of relevant conceptual resources is a necessary but insufficient condition for the formation of expert-like assemblages (Bransford et al., 2000; Brock, 2018; Kosso, 2002). For example, in considering a mass on a spring, Ben, possessed the resources needed to produce the accepted explanation of the object's motion. In earlier sessions, he had correctly applied Newton's first law, could describe how the force exerted by a spring varied with displacement, and had activated, in some contexts, the canonical assemblage of the relationship between net force, acceleration and velocity.

Students' difficulties in forming stable expert assemblages can arise at several stages of the assembly process. They might lack necessary conceptual resources, activate alternative conceptions in preference to scientific concepts, or fail to activate assemblages in the same contexts as experts. Whilst these challenges, which focus on the resources novices possess and their activation, have been the subject of much research attention, the process of assembly has been less studied. Novices may be attempting to assemble units that differ from those of experts (Edward's explanation of the motion of the ball in the bowl drew on a conflated force and momentum resource) and hold different expectations about the coherence of resources ('… it doesn't always make sense' (Edward, Session 1)). In our analysis we examine three aspects of the assembly process. First, we consider how students' perceptions of the boundaries of resources impact their ability to organise elements. Second, we examine how students' epistemological assumptions may influence assembly (Hammer et al., 2005; Hammer & Elby, 2003; Sherin et al., 2012). Finally, we consider the stability of assembled elements.

First, how conceptual resources are perceived will impact how they are assembled. It is tempting to assume that expert conceptual resource boundaries can be applied to representations of novice cognition, that is, in our analogy, that novices have the same materials to make their collages as experts. However, novices and experts may perceive different divisions in conceptual resources (as in Charlie's assemblage of gravity/weight or Ben's perception that all energy is kinetic). The perception of conceptual units is dependent on expertise (Chase & Simon, 1973; Simon & Chase, 1988). Alternative categorisations have consequences for learning, novices' assemblages can differ from experts' because they are assembling different elements. Researchers could be cautious about their assumptions about the entities they infer from data, what is assumed to be unitary for a researcher (for example, a participant's concept of force) may be fragmented to a participant (Hammer et al., 2005). When researchers represent units in research data (for example, concepts), they should discuss assumptions and, where applicable, present empirical evidence about the boundaries and stabilities of those elements.

Second, the assembly process may be influenced by beliefs about the nature of desirable assemblages, that is by epistemological assumptions (Hammer et al., 2005). Just as an artist has criteria for judging the aesthetics of created collages, so learners make judgements about the coherence of their assemblages, and the criteria for these judgements may differ from those of experts (as in the case of Ben, Edward, and Charlie's assumptions about coherence). Both in research studies and in the classroom, the assembly model suggests assessment of expertise cannot be based on reports of the presence or absence of isolated conceptual resources in a narrow range of contexts. Descriptions of assemblages in response to some probe, at one time, should be assumed to be potentially only one of several responses available. Teachers and researchers might probe for the presence of alternative assemblages by asking questions such as 'Do you have another way of thinking about this situation?' Multiple, spaced probes in the same context, and different contexts that in experts might elicit similar assemblies (for example, contexts related to harmonic motion, a pendulum, mass on a spring and so on) can provide information on the stability of assemblages.

The stable activation of expert-like resources and assemblages is an important goal of science education, but few studies have reported data on changes to students' activation of collections of conceptual resources, especially over the relatively short time frames of relevance to teachers (for example, the days and weeks between lessons) (Brock & Taber, 2017). Teachers and researchers should consider the extent to which their data collection approaches allow inferences to made about the stability of both the elements and assemblages that students construct. When collecting evidence of learning, either for research or for teaching, assessors should be alert to the possibility that a representation of cognition inferred represents an unstable construct to which the student has limited commitment. If assessment of expertise is not based on data related to students' construction of assemblages in a range of situations at multiple times, incorrect inferences about stability may be drawn. Pedagogically, teachers should support students to develop stable activations of assemblages (rather than being satisfied with evidence of a small number of correct constructions, in a narrow range of contexts). For example, teachers might plan activities in which students form assemblages in responses to related contexts (for example, cases of simple harmonic motion), provide feedback on the assemblages constructed, and highlight relationships that match experts' assemblages. By comparing assemblages constructed at different times, a teacher can determine stable and unstable aspects of student assemblages, and highlight features of contexts that trigger non-canonical assemblages. Such feedback may support the stable activation of expert-like assemblages.

Conclusions

Research into conceptual change in science education has moved from cataloguing students' alternative conceptions in various domains towards modelling conceptual change as variation in a system of conceptual resources. This trend is at an early stage – the research programme currently lacks fine-grained representations of learners' activation and relation of conceptual resources over extended periods of time. This gap may have arisen because of two challenges, one methodological, and one theoretical. First, the variability of the novice assembly process, over time and across contexts, requires extended data collection approaches, which are demanding for researchers and participants. Second, representing learning as an assembly process requires units and structures to be represented in research data, the issue we draw attention to in this article. Cognition does not have natural 'joints' – the grain size of conceptual resources varies with expertise (Chase & Simon, 1973; Simon & Chase, 1988). What novices experience as discrete conceptual resources may be treated as a unit by experts, and unitary constructions for a novice may be represented as compound structures by experts (for example, whilst a novice may have a generic concept of motion, experts can differentiate between velocity and acceleration). When researchers discuss the assembly process, data indicating the activation of conceptual resources across contexts and over time can provide evidence of the resources' stability and differentiation from other resources and so justify treating aspects of data as units.

We assume that the representations of learning produced in our study are grounded in the context of the participants, their learning environment, the probes used, and shaped by the assumptions of the researchers. As such, the descriptions may not generalise beyond the cases described. The descriptions of stability and instability were prompted by the context of the interviews and the probes the participants encountered and cannot be assumed to fully represent the stability of underlying cognitive structures. Frequency of activation is an insufficient indicator of stability. Whilst we have used the frequency of activation of a conceptual resource as a proxy for stability, in the absence of direct access to cognitive states, irregular or infrequent activation need not indicate an unstable element in cognitive structure.

The research programme examining the formation of assemblages is relatively novel, and more extensive reports of the processes of formation and dispersal of assemblages are required to develop teaching approaches. Future work might focus on two strands, the description of patterns of assembly, and the development and evaluation of pedagogies that support students' ability to form expert-like assemblages. Work in the first strand might address question such as: what commonalties and differences exist between individual's assembly processes? What aspects of contexts guide the formation of assemblages? Research in the second aspect might pilot approaches to pedagogy of the form set out above and compare their affordances for supporting learning against alternatives. The study of assemblages, and pedagogies to support their development, is a potentially fruitful research programme in science education research.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Ethical statement

The project received ethical approval through the ethical review procedures of the Faculty of Education, University of Cambridge.

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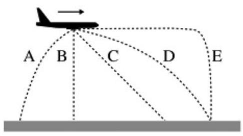
Appendices

Appendix 1: Probes used

Object dropped from an aircraft moving at horizontal velocity (adapted from Hestenes et al., 1992)

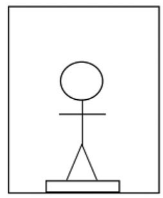
Projectile from a plane, interview 1, 15, 22
(Adapated from Hestenes et al. 1992)

An aeroplane is travelling with constant velocity when it drops a ball. Which path best describes how the trajectory of the ball would look to an observer on the ground? Explain your answer.



Forces on a person in a lift (adapted from Hestenes et al., 1992)

(f) Forces on a person in a lift, Interview 1, 4, 15, 22
(Adapted from Hestenes et al., 1992)



A person travels in a lift whilst standing on a set of scales. Describe the reading on the scale relative to their 'normal' mass in each situation. Label the forces that act.

Simple pendulum

Simple pendulum, interview 2, 15, 22
Student is shown a simple pendulum system

The student is given the following prompts:
• Describe the motion of the bob (sketch graphs of displacement, velocity and acceleration against time)
• Explain the motion of the bob
• Draw a force diagram to illustrate your answer
• Predict what will happen when the mass of the bob is increased.

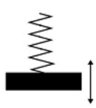
Leaping from a crouched position

(s) Leaping from a crouch, Interview 13
Describe the forces on the person as they leap from a crouched position

Mass on a spring

(i) Mass on a spring, interview 2, 15, 22

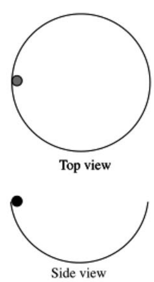
Student is shown a mass-and-spring oscilator



The student is given the following prompts:
• Describe the motion of the mass (sketch graphs of displacement, velocity and acceleration against time)
• Explain the motion of the mass
• Draw a force diagram to illustrate your answer
• Predict what will happen when the mass on the spring is increased.

Ball in a bowl

(m) Ball in a bowl, Interview 5,15,16, 22
Place the marble on the side of the cooking bowl and release it-observe the oscillations



Describe the motion of the ball. Explain its motion. Use the diagrams to support your answer.

Appendix 2: A model solution to the ball in the bowl problem

Two forces act on the ball – gravitational force (the ball's weight), which always acts vertically downwards, and a normal reaction force which acts perpendicular to the surface the ball is placed on.

The net force acting on the ball (ignoring frictional effects) will result from the vertical weight, and the reaction force. The reaction force has a vertical component that increases as the slope of the bowl surface becomes more horizontal, becoming maximum when the slope is exactly horizontal. In addition, the reaction force has a horizontal component that is zero when the surface is exactly horizontal, increases as the slope of the bowl becomes more vertical, then falls as the slope approaches the vertical.

When the ball is placed on the bowl's rim, the surface of the bowl is nearly vertical, so there is only a small reaction force and the net force is directed downwards, slightly off vertical. The net force causes the ball to accelerate. As the ball accelerates down into the bowl, the direction of the reaction force changes due to the curvature of the bowl.

As the surface becomes increasingly horizontal, the reaction force (which balances the component of weight normal to the surface) increases, and the horizontal component diminishes.

The net force on the ball decreases until, when the ball is the centre of the bowl, the normal reaction force acts vertically upwards, perpendicular to the surface and is completely balanced by the gravitational force that acts vertically downwards. At this point, the net force on the ball is zero and it does not accelerate. As the ball is already in motion, it continues to move with constant velocity.

When the ball moves past the midpoint of the bowl, the normal force again has a component towards the midpoint of the bowl. The net force now causes the ball to decelerate until it is momentarily stationary, when the net force is maximum, at its most extreme displacement. The ball then moves off in the opposite direction to its previous motion and the cycle repeats.