29 SYNTONICITY AND EMERGENCE: A DESIGN-BASED RESEARCH REFLECTION ON THE PIAGETIAN ROOTS OF CONSTRUCTIONISM

Dor Abrahamson and Kiera Chase

When thirty-year-old Papert arrived in Geneva in 1958, Jean Piaget's International Center for Genetic Epistemology was already well established. Nicknamed "Piaget's Factory," this industrious institute thrived as a global font for groundbreaking theories of children's cognitive development. These powerful theories shaped Papert's pedagogical vision.

Per Piaget, children arrive in the world with a capacity for learning about the world but little knowledge about it. Coming to know the world is a process neither of direct apprehension and emulation (a "rationalist" view) nor an accumulation of stimulus-response associations (an "empirical–behaviorist" view). Rather, infants' knowledge of the world as they find it is constituted through their own active exploration of the environment: performing motor actions, experiencing their sensory outcomes, and iteratively selecting and refining sensorimotor couplings that promote the attainment of their local humble goals. In so doing, the infants unwittingly become better prepared for subsequent encounters with other situations perceived as similar. Critically, children's perception of what is out there and how they may act on it is bound by, or filtered through, the residue of their prior activity and reflection. Perceiving and therefore knowing are constructed through action. As Piaget (1971) famously stated, "Knowing does not really imply making a copy of reality but, rather, reacting to it and transforming it (either apparently or effectively) in such a way as to include it functionally in the transformation systems with which these acts are linked" (p. 6).

Infant knowledge is thus constituted not as subject–object dualism, that is, what *I* know about *something*, but as an intrinsically relational scheme, where perception and action co-adjust adaptively, iteratively assimilating the world to achieve enhanced capacity for effecting change benefitting the organism. Knowledge, or rather *knowing*, is foremost prereflective, presemantic, presemiotic, presymbolic, situated modal capacity: an ad-hoc cognitive construction that is inherently subjective, contextual, and relational. Knowing is constituted and reconstituted in its enaction, and the world comes forth for us only inasmuch as we have formed capacity to engage it in ways pertaining to our individual needs and interests.

The child's early operative structures, the schemes, enable, regulate, and constrain the child's anticipation, interpretation, and response to events. At the same time, these structures are permeable, flexible, and modular. They may become either generalized or differentiated as necessity occasions the child in natural and sociocultural environments, and they may be mixed and matched to form more complex superstructures when coordinating two or more such schemes proves vital for overcoming an impasse to attaining a goal. When concerted cognitive effort is required to resolve a puzzling situation—when we *stop to think*—hitherto ineffable structural qualities of our cognitive schemes may rise to conscious reflection as meanings that lend themselves to discursive reference. Therewith these schemes become amenable to signification, elaboration, and evocation in the sociocultural linguistic context.

What might it mean, given this provocative theory of mind, for a child to learn cultural notions traditionally considered as transcending the material world, such as mathematical concepts? How might a sensorimotor organism come to know the would-be abstract idea of algebra? What might be the primitive transformational systems undergirding a child's conception of formal disciplinary knowledge that is normatively encoded in arbitrary symbolic notation? In turn, to the extent that endorsing these cultural forms requires a child to negotiate epistemic rupture from their naïve knowing of situations to techno-scientific structurations of these same situations, what pedagogical intervention might prove useful for mending this rupture? In particular, what technological artifacts, activities, and environments might foster epistemic continuities between a child's sensorimotor schemes and the formal routines of mathematics (what Papert called "civilization's crowning jewel of achievement")? These enduring theoretical and practical questions have shaped the careers of numerous educators informed by Piaget's theory. For Papert, it was questions such as these that drove the pedagogical vision of constructionism.

In this chapter, we wish to highlight two big philosophical-cum-educational ideas—intellectual veins—that, we argue, run from Piaget's epistemological cosmos through Papert's pedagogical universe to current design-based research on STEM learning and into the future. Both ideas are about the nature of human learning. Yet, as design-based researchers, we will paint one idea, *syntonicity*, as more about informing a general design rationale guiding the process of envisioning technological environments for learning, in particular via the framework of *embodied design*. The other idea, *emergence*, is more about the analytic work of modeling empirical data collected in these studies in terms of the cognitive growth they implicate, in particular through paradigms and methods of coordination dynamics. Following a section, below, that presents these two powerful ideas, we will exemplify them in the context of a technological design for early algebra, Giant Steps (Chase & Abrahamson, 2018). The chapter will then end with a conjecture on the future of educational research informed by syntonicity and emergence.

TWO POWERFUL IDEAS: SYNTONICITY AND EMERGENCE

By coining the phrase "powerful ideas," Papert signaled both that young minds are prepared for complex intellectual encounters and that designers should facilitate these encounters. One big idea about learning is an insistence on designing environments that maximize potential for concordance with a child's tacit enactive capacity in natural and cultural ecologies, an idea Papert (1980) called *syntonicity* (i.e., body syntonic, culture syntonic). As a pedagogical heuristic vying with Piaget's genetic epistemology (Piaget, 1968), *body syntonicity* calls for learning activities that draw on the child's intuitive facility in simple situations—what a child knows by virtue of being an experienced, sentient, multisensory, mobile, corporeal, and agentive terrestrial organism. These include the manifold of informal know-how, such as the embodied sensations of somatics, proprioception, orientation, rhythmic movement and coordination, perceptual judgments, the recognition and manipulation of generic objects, rudimentary quantitative reasoning, heuristic inferential routines and biases, and basic navigation and action in the peri-personal space and beyond. *Cultural syntonicity* encompasses facility with facets of familiar individual and social practices involving artifacts and joint action, such as sailing, juggling, hiding and chasing, singing a tune, decorating a house, telling a story, dancing together, preparing food, planning a hike, or engaging in a basic commercial transaction.

For educators, syntonicity specifies that formal representational structures, such as hierarchical systems of computational procedures for information technology, be couched and introduced to a child such that they pertain not to immaterial forms serving obscure functions. Rather, these complex structures should be couched such that they pertain foremost to familiar objects and meaningful situations—to things that can be perceived and handled toward some ends that are coherent, meaningful, and engaging. Learning to program could thus initially be not about figuring out the most efficient algorithm for sorting a list of numerical values but about using stuff to build a thing that does something, such as writing a Logo program that gets the turtle to paint a rainbow. The same would go for mathematics.

Another powerful idea we see Papert offering educational scholars and designers is that of *emergence* as an intellectual paradigm for investigating the evolution of adaptive, stable, and self-regulating complex dynamic systems, be these natural, social, or cognitive phenomena. Piaget's genetic epistemology is inherently systemic (Piaget, 1970), in that he formulates a theoretical model accounting for the process by which simple knowing evolves into sophisticated knowing, where each construction either modifies or coordinates existing structures vis-à-vis shifting situated goals. These adapted cognitive structures thus self-accommodate to assimilate variation in environmental encounters, where difference is perceived as either similarity or novelty. As such, the child's world is a goal-oriented systemic construction, where haphazard contingencies ever constrain the pruning, specialization, and assembly of better-adapted coping mechanisms. Learning in the natural and cultural–historical social ecology is nondeterministic, nonlinear, nonteleological genetic evolution, in which stable environments nurture and regulate individuals' inherent capacity into fully adapted wherewithal, complete with linguistic, quantitative, technological, and moral aptitudes.

Papert sought to further refine Piaget's model of cognitive development by proposing a principle for the organization of schemes into hierarchical clusters ("Papert's principle," see Minsky, 1985). This structuralist epistemological model strove to characterize cognitive development, such as the conservation of volume, as an iterative optimization search process, in which primitive judgment aptitudes (e.g., "taller-than," "wider-than") are exploratively grouped by family resemblance to make salient within-situation critical conditions for inferring properties in question ("more-than" or "same"). Emergent superstructures, such as the idea that material quantity is conserved when no substance was added or removed, consolidate iteratively through empirical proof of their replicability, validity, and utility.

An epistemological theory that acknowledges the essentially emergent quality of cognitive development appears to imply a pedagogical approach that recognizes a need to provide for each child's idiosyncratic path, even as it guides all students toward common-enough knowledge and skills. Such a pedagogical approach might lead to *restructuring* curricular subject matter content (see Wilensky & Papert, 2010), such as rudimentary algebra, not only to render it body/culture-syntonic but also to cater for the emergence of content knowledge as a cluster of simple cognitive structures self-assembled to serve greater conceptual objectives. This multischeme assembly process would be mutually interadaptive, where a set of relevant schemes evokes, interconstrains, and prunes each other, as gauged vis-à-vis its global replicability, validity, and utility, into a functional transformation system. This evolving cognitive system would be manifest for external observation in the child's adaptive behavior, culminating in the fluent enactment of solutions for a class of situations presented in educational activities, such as algebra problems bearing unknown quantities.

What might all of this theorizing look like in the form of actual learning resources? True to this volume's orientation on constructionism in context, the remainder of this chapter will attempt to support the argument for the dual legacy of syntonicity and emergence, from Piaget through Papert and beyond, by discussing a more recent educational design-based research project that was nurtured by these big ideas. The project in question may not be a paradigmatic exemplar of constructionist pedagogy, in that it was not conceived to permit children full sway in pursuing and manufacturing their own worlds. Rather, the educational design in question is far narrower in its pallet of actions and building choices offered to the child than, say, a Logo microworld. Yet it does aspire to constitute a body- and culture-syntonic environment, and students' experiences therein lend themselves auspiciously to systemic modeling of learning as the emergence of a cluster of interconstraining schemes. Following a section on the project, below, we will offer some observations on the future of educational technology inspired by constructivist/constructionist principles and, perhaps, taking them one tiny step farther.

GIANT STEPS FOR ALGEBRA AS A MODEST EXAMPLE OF CONSTRUCTIONIST PEDAGOGY: A CASE FOR SYNTONICITY AND EMERGENCE AS POWERFUL IDEAS FOR DESIGN-BASED RESEARCH

Giant Steps for Algebra (GS4A, Chase & Abrahamson, 2018) was a design-based research doctoral dissertation project conceived as a response to the problem of US students' underachievement in mathematics, particularly in algebra. Viewing this enduring national problem as a challenge to educational practice, many researchers have implicated students' cognitive difficulty in transitioning from arithmetic to algebra: Whereas arithmetic curriculum typically fosters the conceptualization of equivalence ("=") as *operational*, that is, an action "on the left" with a result "on the right," algebra requires a *relational* conceptualization of equivalence between two quantities. As design-based researchers of mathematical cognition, teaching, and learning, we chose to explore pedagogical solutions with the potential to better pave the arithmetic-to-algebra learning transition.

Our first task was to investigate existing algebra curricula so as better to understand current pedagogical approaches and perhaps glean their underlying epistemological assumptions and conceptual structuration. This initial analytical process revealed to us the *balance metaphor* as the most common educational introduction to the relational structure and logic of algebraic equations. The balance metaphor is typically presented to students by invoking interactions with relevant cultural artifacts, such as the twin-pan balance scale. Yet whereas balance scales per se appear to be *body* syntonic, in that they draw on an embodied sense of equivalence, it is not clear whether this particular sense enables students to build from their robust arithmetic skills toward the relational conceptualization of algebraic equations. Moreover, twin-pan scales are increasingly substituted with electronic scales so that their alleged *cultural* syntonicity may be lost to the target audience of algebra learners.

Further search of the literature revealed that Dickinson and Eade (2004) had tackled a similar design problem by using the double number line as a diagrammatic form for modeling linear equations. Figure 28.1 shows a fragment from our GS4A adaptation of their model into a dedicated microworld (later in this section we explain additional elements in this figure). The GS4A problem narrative depicts a quasi-realistic situation, in which a giant performs two consecutive journeys along a path. The narrative for the figure 29.1 example reads as follows:

> A giant has stolen the elves' treasure. Help the elves find their treasure! Here is what we know. On the first day, the giant walked 3 steps and then another 2 meters, where she buried treasure. On the next day, she began at the same point and wanted to bury more treasure in exactly the same place, but she was not sure where that place was. She walked 4 steps and then, feeling she'd gone too far, she walked back one meter. Yes! She found the treasure!

Thus, these two journeys—Day 1 journey and Day 2 journey—begin at the same point of departure (the "START" flag on the left) and end at the same destination (the treasure flag on the right). However, the journeys differ in terms of the agent's process. The two journeys correspond to two equivalent algebraic expressions: here the algebraic proposition "$3x + 2 = 4x - 1$" is rendered into the progressions "$3x + 2$" (Day 1 above the line) and "$4x - 1$" (Day 2 below the line).

Our evaluations of the activity with pre-algebra study participants suggested the syntonic design quality of students diagrammatically modeling

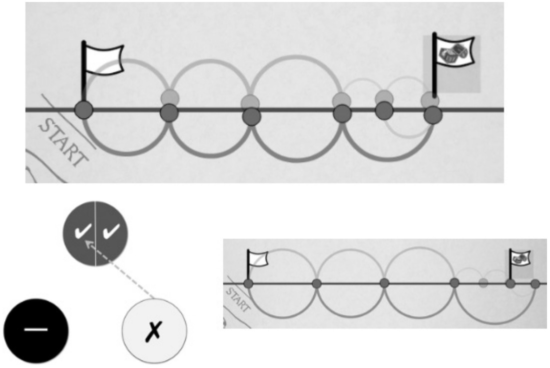

FIGURE 29.1
Giant Steps for Algebra: example of diagrammatic activity and its cognitive modeling. *Above:* A student's first attempt at solving a narrative instantiation of the algebraic proposition of $3x + 2 = 4x - 1$. On both Day 1 ($3x + 2$, above the horizontal path line) and Day 2 ($4x - 1$, below the line) the giant traveled from the "START" flag on the left to the Treasure flag on the right. Red arcs represent giant steps (the variable x), and green arcs represent meters (the fixed integer units). In building this diagram the student has apparently attempted to maintain consistent measures (SILO 1) of giant steps and meters, respectively, but has not achieved equivalent expressions (SILO 2) above and below the line (note different end points of Day 1and Day 2 journeys), consequently failing to create a shared frame of reference (SILO 3). *Bottom-left:* The student's current conceptual knowledge state, as evident in their diagram, is modeled as an emergent system composed of these three interconstraining schemes. The arrow depicts the student's consequent inference, as evident in their subsequent modification of the diagram that repaired the violated equivalent expressions by readdressing the consistent measures, thus achieving a shared frame of reference that led to calculating the size of a giant step in this particular narrative as 3 meters.

an algebraic text narrative. First, the pilot study corroborated prior findings from psycholinguistics research that text-comprehension processes are enactive–imagistic (e.g., Zwaan, 2004) as witnessed in the participants' multimodal utterances and construction actions. Engaging with the narrative brings forth body-syntonic know-how. This tacit knowing becomes reified, conscious, modified, and combined by virtue of depicting the narrative as a perceptually durable and shareable display upon the interactive virtual canvas. Second, the study suggested that students can develop new forms of mathematical reasoning capacity through constructing and adjusting given resources into a depictive diagram (Martin & Schwartz, 2005). Students act on features in the GS4A interface, interpret products of these actions, and then act again, a design process that Bamberger and Schön (1991) call "see–move–see."

What types of body- and culture-syntonic know-how did the participants bring to bear in depicting the text narrative? What were their situated abstractions (Noss & Hoyle, 1996)? What cognitive models emerge through this process? As researchers who develop instructional resources with well-defined curricular goals in mind, we chose to name children's proto-conceptual know-how *situated intermediary learning objectives*, or *SILOs*. Our micro-analyses of the video and screen data suggested the following three SILOs.

1. *Consistent measures*. All variable units (giant steps) and all fixed units (meters) are respectively uniform in size both within and between expressions (days).
2. *Equivalent expressions*. The two expressions (Day 1 and Day 2) are of identical magnitude—they share the "start" and the "end" points, so that they subtend precisely the same linear displacement (even though the total distance traveled may differ between days, such as when a giant oversteps and then goes back).
3. *Shared frame of reference*. The variable quantity (giant steps) can be described in terms of the unit quantity (meters).

As cognitive constructs, the SILOs thus hover in an epistemic space between the locally pragmatic and the conceptually generative. SILOs are thus expressed both as embodied experience and cognitive constructs—both contextual and universal—grounded both in body-syntonic know-how, such as assuming that by default the giant struts along in equally sized strides, and culture-syntonic methods, for example using conventional arbitrary units, such as meters, to measure linear extension. The SILOs render cognitively *transparent* the operational logic of procedural actions in an otherwise opaque activity structure such as algebra. The construct of *transparency* (see Meira, 1998) captures the psychological relation between an individual and the artifact they are using toward the accomplishment of some goal. We say that the artifact is transparent to an individual when he or she has developed an understanding for how its embedded features function to promote the accomplishment of its systemic objective. The SILOs distil and render transparent the operational logic of GS4A algebraic problem-solving mechanics. By engaging conscientiously with the GS4A activity, students achieve the design's SILO system, thus mentally constructing procedures for creating and maintaining equivalence, even as they literally construct and debug a solution model for a problem narrative (see figure 29.1 and Chase & Abrahamson, 2018, for results from analyses of empirical data gathered in experimental design interventions).

Let us now turn to emergence as a principle for modeling the evolution of students' cognitive growth through working in the GS4A environment. Above, we have described each of the three SILOs as logically independent. And yet our analyses revealed that the process of constructing each SILO is ontogenetically interdependent upon the process of constructing the other two SILOs. In particular, the SILOs niche ecology coalesces iteratively, through ongoing reflective practice of iterating on the depictive model, with each SILO constraining the emergence and calibration of the other SILOs (Chase & Abrahamson, 2018).

By design, users build algebra as a transparent practice. This design consisted of a task, resources, and a specific activity flow that scaffolded for the emergence of mathematical cognition. In Chase and Abrahamson (2018), we coined the phrase *reverse scaffolding* to capture our pedagogical methodology for guided emergence of mathematical concepts in technological environments, where instructional-interaction decisions are implemented in software procedures. The *reverse scaffolding* design architecture works as follows. Once students' diagrammatic construction makes evident that they have successfully generated and managed a mathematically appropriate structural property of their model (i.e., they have achieved one of the SILOs), the software "takes over" by automatically enacting and maintaining this property for them. When students initially encounter the GS4A interface, they must manually construct and monitor all structural aspects of their diagrams, such as ensuring that all giant steps are equivalent. Yet once a student articulates a SILO—perhaps commenting that giant steps are uniform—the interface responds by entering a new "game level," in which the giant step is automatically produced for the user and changing one giant step uniformly changes all other giant steps on the screen. Crucially, *reverse-scaffolding designs perform for users only what they already know to do, not what they are not able to do, as in mainstream applications of the scaffolding metaphor*. Reverse-scaffolding interface actions are thus designed to promote student agency in the emergent construction of their conceptual systems.

The *reverse scaffolding* design was conceived as a pedagogical approach that could straddle the divide between purist constructivist learning approaches and automated educational technologies. We want students to discover, invent, and engage an emergent network of interconnected schema, and, yet, we acknowledge that continuing to reinvent from scratch can become tedious. Conversely, if educational technologies automate and scaffold users' production and process from the start, these functions are liable to remain opaque to the user, effectively robbing users of the opportunity to construct their own understanding. The reverse-scaffolding activity architecture enables the emergence of the cognitive superstructure for early algebra, through the iterative consolidation and systemic interconstraining of each SILO.

To our evaluation, the GS4A project made both practical and theoretical contributions aligned with principles of syntonicity and emergence carried down by Papert from Piaget. Both theoretically informed and developmentally appropriate, educational designs based on the interactive diagrammatic modeling of narratives create opportunities for students to elicit and build their situated knowing into transparent, functional conceptual structures that expand their capacity to engage in the cultural practices of mathematics. Furthermore, the design-architecture notion of reverse scaffolding creates for educators a template to plan for the sequential emergence of students' conceptual knowledge. Finally, students' learning process as well as researchers' analysis process are organized around the cognitive construct of SILOs, situated intermediary learning objectives, thus making for coherent design-based research studies of mathematical cognition, teaching, and learning.

MOVING FORWARD: COORDINATION-DYNAMICS RESEARCH ON THE EMERGENCE OF KNOWLEDGE FROM SYNTONIC DESIGN

> Plus ça change, plus c'est la même chose
> (Jean-Baptiste Alphonse Karr, 1849, *Les Guêpes*)

Papert did not like education. At least, he disliked how this word connotes that somebody is doing something to a child, whereas in fact it is the child who is learning. And so rather than "pedagogy," Papert (1980) spoke of *mathetics*, "the set of guiding principles that govern learning" (p. 52). An "applied mathetician," Papert is mostly known as a learning futurist, a diviner of all things to come in learning technology, one who sedulously practiced the adage, "The best way to predict the future is to invent it" (attributed to Alan Kay). Yet while Papert was busy inventing the practice future of body/culture-syntonic learning, the theory slow coach of cognitive sciences considered resonant ideas on embodiment that, in turn, seeped into educational research as embodied design (Abrahamson & Lindgren, 2014).

Embodiment perspectives in educational research by and large reinstitute Piaget's post-dualist systemic theory of cognitive developmental psychology by underscoring the constitutive role of sensorimotor activity in the emergence of adaptive coping in natural and cultural ecologies. Accordingly, embodied design is a heuristic methodology for creating learning environments, including materials, tasks, and facilitation guidelines, wherein students are ushered to spontaneously appropriate legacy cultural methods as powerful means of enhancing their innate or early developed sensorimotor capacities, such as perceptual judgments or motor coordination. Indeed, laboratory evaluations of an action-based embodied design for proportions have corroborated empirically a central tenet from Piaget's genetic epistemology, reflective abstracting. Combining eye-tracking and clinical data, we demonstrated the emergence, and then the verbal articulation, of new dynamical perceptual structures that came forth as gestalts in the child's imagined visual display to coordinate spontaneous solutions for bimanual movement problems (Abrahamson, Shayan, Bakker, & Van der Schaaf, 2016). We view this design-based research as extending the theory of coordination dynamic (Kelso, 2014) into conceptual realms of human capacity.

Even as theories of learning change, they could be essentially more of the same thing. Piaget might call this a type of conservation that we come to appreciate through intellectual interaction. As a framework for building learning environments, embodied design attempts to implement Papert's notion of syntonicity that, we have argued, in turn realizes Piaget's insight into the emergence of knowledge through situated interaction. Notwithstanding, things do change in important ways, even as they remain the same. Constructionism has changed the way we think about designing for learning, as we believe the Giant Steps for Algebra project has demonstrated. If we build designs, the students will come. If students build artifacts, they will construct powerful ideas.

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