MODELING IN ETHNOCOMPUTING: REPLACING BI-DIRECTIONAL FLOWS WITH RECURSIVE EMERGENCE

MODELAGEM EM ETNOCOMPUTAÇÃO: SUBSTITUINDO O FLUXO BIDIRECIONAL PELA EMERGÊNCIA RECURSIVA

Michael Lachney
michael.lachney@gmail.com

Audrey Bennett
bennett@rpi.edu

Rensselaer Polytechnic Institute

Jorge Appiah
jorgeappiah@gmail.com

Kwame Nkrumah University of Science and Technology

Ron Eglash
eglash@rpi.edu

Rensselaer Polytechnic Institute

ABSTRACT

Ethnocomputing is the study of the intersections between culture and computing. In addition to cultural analysis of computing, it also utilizes computing to model artifacts or practices from a given culture. In this essay, we consider three *modes* of modeling. In the first mode, the knowledge flow is unidirectional: the researcher analyzes indigenous designs and provides a computing model. In the second mode, the knowledge flow is bidirectional with researchers bringing a technical etic (outsider) perspective and informants bringing a cultural emic (insider) perspective. In the third mode, knowledge flow is recursive; there are bidirectional flows nested within other bidirectional flows. Our case study begins with computer simulations of log curves in Adinkra symbols in Ghana. Thus, we show that there are nested flows between nature and the indigenous artisans who model nature's growth patterns; between our own ethnocomputing simulations and the students and teachers in Ghanaian classrooms; and finally between the history of computing in the West and the implementation of educational technology. Our data indicates that a recursive model that can account for these nested flows better enables researchers to integrate social justice and sustainability with education and research in both social and technical domains.

Keywords: Agency; Ethnocomputing; Indigenous Design; Modeling; Translation.

RESUMO

A etnocomputação é o estudo das interseções entre a cultura e a computação. Além da análise cultural da computação, a etnocomputação também utiliza a computação para modelar os artefatos ou as práticas de uma determinada cultura. Nesse ensaio, consideramos três "modos" de modelagem. No primeiro modo, o fluxo do conhecimento é unidirecional, pois os pesquisadores analisam os modelos indígenas e fornecem um modelo computacional. No segundo modo, o fluxo de conhecimento é bidirecional, pois os pesquisadores trazem uma perspectiva ética técnica (de fora) e os informantes trazem uma perspectiva cultural êmica (de dentro). No terceiro modo, o fluxo de conhecimento é recursivo, pois existem fluxos bidirecionais aninhados em outros fluxos bidirecionais. Esse estudo de caso começa com as simulações computacionais dos registros de símbolos curvos Adinkra de Gana. Assim, mostramos que existem fluxos aninhados entre a natureza e os artesãos indígenas que modelam os padrões de crescimento na natureza; entre as nossas próprias simulações etnocomputacionais e os alunos e professores nas salas de aula em Gana e, finalmente, entre a história da computação no Ocidente e a implementação da tecnologia educacional. Os dados indicam que um modelo recursivo que considera esses fluxos aninhados possibilita aos pesquisadores uma melhor integração da justiça social e da sustentabilidade com a educação e a pesquisa em ambos os domínios social e técnico.

Palavras-chave: Agência; Etnocomputação; Esboço Indígena; Modelagem; Tradução.

1. Introduction

Ethnocomputing is an interdisciplinary research program that is concerned with the intersections of computing and culture wherever they come together: indigenous communities, academic research groups, classrooms, corporations, etc. (Eglash et al. 2006; Sutinen & Vesisenaho, 2006; Tedre & Eglash, 2008; Kafia et al., 2014; Babbitt et al., 2015). Often it utilizes mathematical or computational modeling in a one-way knowledge flow: natural or artificial pattern X can be modeled with Western mathematics practice Y. Recently Rosa and Orey (2013) proposed a bi-directional modeling process in which indigenous and western knowledge inform each other.

In this chapter, we introduce a third model, which is recursive. That is to say, there are bi-directional flows within indigenous culture (such as the interaction between nature and humans); and bi-directional flows within western culture (such as the interaction between people and machines). Bringing those together results in a recursive modeling process; a nesting of flows within flows. We use a case study of our collaboration between United States ethnocomputing researchers and Ghanaian schools and artisans to provide evidence that this recursive mode of knowledge flow offers strong advantages for both improving student learning, as well as decolonizing math and computing education in both Western and non-Western contexts.

2. The First Two Modes of Modeling Indigenous Design

Each of the three modes (unidirectional, bidirectional, and recursive) can be understood as relationships between the *emic* and *etic*. The emic view is that of the indigenous perspective, the view from inside the culture. Of course, that can be very heterogeneous when taking into account gender, class, historical moment, etc. but we will refer to it as unitary for clarity. The term *etic* is the outsiders' perspective, and likewise involves the complexities of identity and positionalities. These complexities are often underreported because those of us working at the intersections of STEM[1] and social justice are typically up against mainstream assumptions about *primitive cultures* or other colonial constructions. So, we often aim for a simple story — *the quipu was an ancient Peruvian data structure* — because we worry that teachers will not have time for complexity; skeptics will pounce on less firm statements; etc. In this essay, we strive to offer an opposite case: that a more complex portrait can sometimes offer a more effective basis for progressive social change.

The first process to consider is the unidirectional mode, which is typically employed in the discipline of *mathematical anthropology*. Mathematical anthropology produces ethnographic and archaeological data to model the patterns of indigenous designs and knowledge systems within Western mathematical traditions, often without attributing intentions to the communities where the design takes place (Eglash, 1997). Instead, patterns are described as unintended consequences of social dynamics and collective behaviors that are contextualized by the natural world (Kay, 1971).

For example, Alan Koloseike (1974) explains the mud terrace construction in Ecuador as an unintentional by-product of agricultural activities and erosion. It is not simply that he fails to find evidence for intentional activity; rather he carefully details the case for why intentional involvement can be eliminated, and explains that mathematical modeling of the rate of mud terrace growth can only be accomplished once indigenous awareness has been eliminated as playing any causal role. We refer to this false dichotomy as *methodological distancing*: there is no reason why a mathematical model that is based on erosive accumulation cannot include the possibility of an *indigenous counterpart* or conscious reflection on the part of communities who shape their own material conditions from generation to generation (Eglash, 1997).

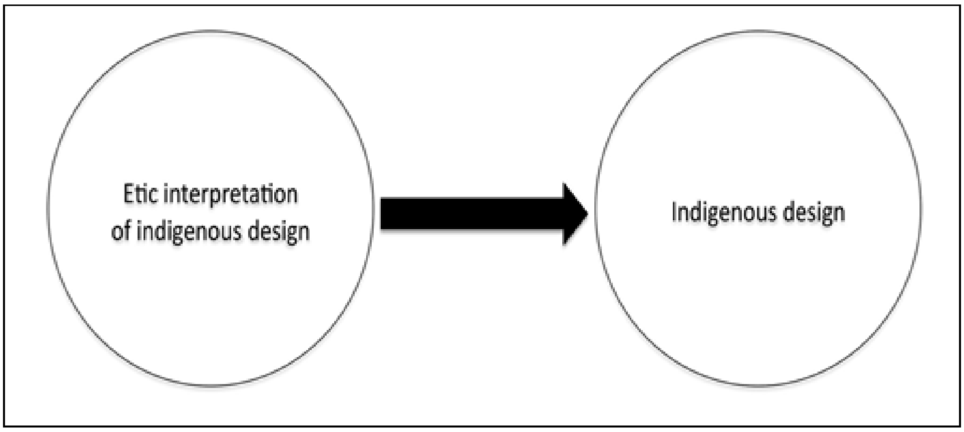

Figure 1. Unidirectional knowledge flow of indigenous design in mathematical anthropology

[1]STEM (science, technology, engineering, and mathematics) is an acronym used in policy and curriculum to describe an interdisciplinary approach to education. It is often invoked in US policy to discuss "improving" national workforce and security.

Figure 1 shows this methodological distancing in mathematical anthropology as a unidirectional process that imposes a strictly Western, etic interpretation of indigenous design. It is clearly unnecessary: Koloseike's terraces could easily be modeled as the result of dynamic interplay between unintentional nature and intentional humans[2]. The unidirectional mode ultimately disempowers the indigenous communities in question by silencing the possibility for their own mathematical heritage. This leaves much to be desired in terms of a framework that accounts for indigenous communities' artifacts and practices.

Rosa and Orey (2013) use the language of dialectics to describe their work on *ethnomodeling*, aiming for a bidirectional synthesis of emic and etic interpretations. Their analysis focuses on wine barrel production in Brazil, which originates in the early twentieth century from the techniques of Italian immigrants. They found that wine producers construct barrels using specific cuts of wooden staves to create a perfect fit for a pre-established volume. They do so using an approximation, which simplifies calculation. They compare this formula with one they supplied, which replaces the approximation with an exact measure. They conclude that both interpretations are essential for understanding the ways social and cultural behaviors shape mathematical ideas and practices.

This is an obvious improvement on the unidirectional approach - we can now credit wine barrel makers for mathematics innovation, apply their insights to curriculum development for children in their community, and, as Rosa and Orey (2013) phrase it, prevent "a diversity of skills, technologies, and cultural artifacts, problem solving strategies and techniques, and expertise... [from being] lost to all of us before being understood" (p. 78). On the other hand, this approach still has some troubling asymmetry.

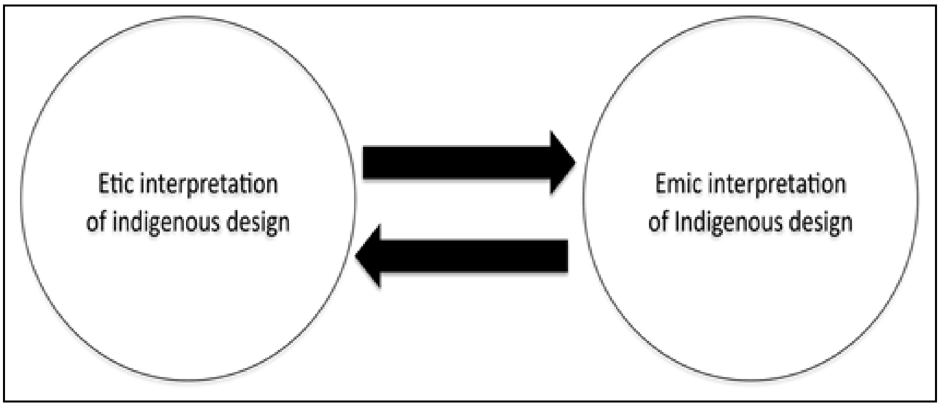

Figure 2. Bidirectional knowledge flow of indigenous design in ethnomathematics and ethnomodeling research

The culture of the wine barrel makers includes mathematics, but where is the culture of the academic mathematicians? Rosa and Orey (2013) suggest that the barrel makers' viewpoint "clarifies intrinsic cultural distinctions while the etic perspective seeks

[2]Science studies theorists have characterized nonhumans — animals, plants, machines, rivers, etc. - as having agency, but not intentionality (Pickering, 1990). Unlike traditional notions of agency that frame practical action as a consequence of human intentionality, these theorists include nonhuman agency as part of the "mangle" in which humans are acting and being acted upon in the material world.

objectivity as an outside observer across cultures" (p. 75). But, isn't the positioning of Western outsiders as more objective, working universally across all cultures, consistent with the very colonial tradition they are criticizing, the *conquering gaze from nowhere* (Haraway, 1988)? The barrel makers have an approximation - a mathematical form, which Rosa and Orey rightly characterize as emerging in temporal process from a locally specific history and economics. However, it is problematic to assume that the academic form is the opposite: something outside of time and space: final, perfected, ahistorical, and universal. Showing how Western science, mathematics and computing is also culturally specific is integral to any critique of its social justice dimensions.

3. The Recursive Mode of Knowledge Flows: A Western Knowledge Case Study

Because of these problems of asymmetry in the bi-directional model, we propose a third mode of knowledge flow, which is based on a recursive structure. We will illustrate this framework using our work comparing logarithmic spirals in the case of indigenous design in Ghana with our historical analysis of the related family of nonlinear forms in Europe. We do so in three steps. First, we will describe how the Western account of logarithmic spirals is not in a final, ahistorical or universal form, but rather a continuously evolving *trialectic* (Eglash et al., 2006) between science and technology, its sociocultural context, and the natural world[3].

In the next section, we show that a similar triad of emergent processes has taken place in the invention of logarithmic spiral models in the Ghanaian tradition of Adinkra, but with an emphasis on sustainable alliances with nature rather than imposing linear control over nature.

Finally, in section five we introduce our ethnocomputing research project, *Adinkra Computing*. It is here that the reader can see the recursive mode fully fleshed out: not a final static form but one that can use the insights of Rosa and Orey (2013) to describe an evolving dynamic that brings Western and non-Western modeling together. We hope this will help facilitate a move toward social justice and environmental sustainability for the relations between nature, culture, and computing.

To fully understand the Western mathematical context for spirals we have to go back to ancient Greece. In Plato's philosophic cosmology, spiritual perfection lies in a transcendent *realm of the forms* where all remains fixed and unchanging. His mathematics was aimed at supporting this view. As Gosling (2010) put it, "Plato's mathematics were essentially static. They were suitable for expressing unchanging configurations and relationships" (p. 92). Thus, it is no surprise that the spiral form that was most important to this culture was the linear *spiral of Archimedes*, in which the space between revolutions never change as you move along a ray from the center.

Fast-forward to 1705, and we still find a similar emphasis: Jacob Bernoulli, who discovered the constant e, requested that a logarithmic spiral would be engraved on his tombstone. But his request failed; the engraver could only supply a linear Archimedean spiral (Figure 3). Here cultural emphasis trumps mathematical innovation. This

[3]There is nothing special about the number 3. One can carry out analysis of *n-alectics* to any arbitrary number, including (as does Barad (2007) the "monist" assumption that 1 is the special number. All are compatible with a model of recursive emergence.

emphasis on mathematics that focused on linear, unchanging and static order was deeply embedded in European culture.

Figure 3. Jacob Bernoulli's tombstone with the wrong spiral (Sojka)

For example, 19th century statistician Adolphe Quetelet (1835) describes his concept of the *average man* using the mean value of measured human variables: as Amoore (2013) notes, “the moves made by Quetelet and his contemporaries marked the beginning of a process of authorization of judgments on conduct, habits, and traits contained within statistical data on society” (p. 49).

This also extended to modeling in fields such as biology and economics. Foucault (2002) refers to this in *The Order of Things*, his history of the 17th to 20th century development of theories of representation:

> What I saw was the appearance of Figures peculiar to the Classical age: a ‘taxonomy’ or ‘natural history’ that was relatively unaffected by the knowledge that then existed in animal or plant physiology; an ‘analysis of wealth’ that took little account of the assumptions of the ‘political arithmetic’ that was contemporary with it (p. xi).

Of course, neither European culture nor mathematics are monolithic; ignoring these conflicts was merely an underlying tendency. In many cases, science was forced to confront these contradictions as environmental disasters and social revolutions proved how poorly top-down linear models predict their consequences.

In the 1930s for example, the practice of agricultural plowing in straight linear rows rather than nonlinear contours contributed to a US *dust bowl* that drove 2.5 million into poverty as migrants (Maher, 2000). This contradiction between scientific models based on top-down linear control, and a nature in which self-organizing forms emerge from nonlinear bottom-up processes, could explain why nonlinear scaling forms in nature were so poorly represented in mathematical modeling; indeed it was not until the publication of D'arcy Thompson’s *On Growth and Form* in 1917 that we saw one of the first general mathematical analyses on the topic.

One way to think about this history is that the sophistication of mathematical formalisms in Europe offered opportunities for a kind of *leverage* or capture of agency that mavericks like Bernoulli or Thompson could use for going against the linear grain.

The ultimate leverage against linear assumptions was the mechanic agency of the computer; it was here that nonlinear dynamics exploded into fractals, chaos theory, complexity theory and other contemporary formulations. Mathematician John Franks (1989) made this point in his review of Gleick's famous popular text *Chaos - Making of a New Science*, where he insisted that Gleick had missed "the obvious explanation of the sudden interest" in nonlinear dynamics, which was "the advent of inexpensive, easy-to-use digital computers" (p. 65).

Thus nonlinear modeling has now been fully incorporated within Western math/computing (Eglash, 1998), but only because the agency of computers, a disruptive *technology*, was available to leverage the work of these nonlinear mavericks.[4] Simple examples such as the Fibonacci sequence in spiral plant growth are common in school textbooks. More complex models of organic growth are featured in research programs on the power laws in biological morphogenesis (e.g. West et al., 1997), including computational models of spiral formation (Hargittai & Pickover, 1992; Newell & Pennybacker, 2013).

This history of nonlinear forms (including that of logarithmic spirals) in the west allows us to provide a missing part of the portrait from the bi-directional model: it is not that flows fail to be bi-directional; rather it is that within what appears to be each unitary, homogeneous *side* actually lies more nested flows. We can see that this family of mathematical forms is not final or static: rather it is an on-going subject of research, itself a negotiation of various tensions, arising from more nested flows. Its presence is not abstracted from time and space; we can see the cultural influence of Western social history and ecology as mathematics arises in a particular context. We summarize these conclusions with the first of three parts of our recursive model (Figure 4).

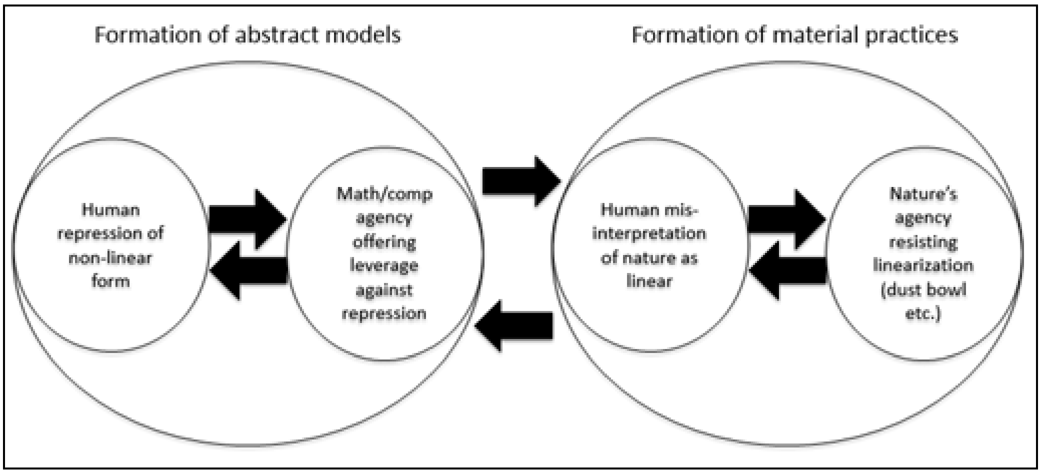

Figure 4. The first of four iterations of our recursive mode of knowledge flow

At the top level, we have a bidirectional relation between abstract models and material practices. However, these are not resting in final balance; as material practices fail, they force new models, which result in new material practices. In addition, nested within

[4] For example Mandelbrot, the father of fractal geometry, famously described himself and other exceptions to the linear trend as such: “he might be called a naive or visionary, but there is a better term in American English: *Maverick*” (1983, p. 392). Subsequently the word *maverick* has appeared in the title of nearly every Mandelbrot biography.

each side is not a unity of models or practices; rather there are nested flows within. Although space only permits us to show this at two levels of nesting, the analysis could be extended to any level that data permits.

For example, in college Jacob Bernoulli was forced to major in theology by his parents; a restriction he greatly resented. Switching to mathematics after graduation was an act of rebellion. Here the causal arrow may have moved from culture to mathematics: his interest in nonlinear forms perhaps inspired by this rebellious rejection of parental religious conservatism. A causal arrow from the other direction: as he gained expertise in mathematics, his relation to his brother Johann moved from collaboration to rivalry (Peiffer, 2006).

Thus, we can think of the equations for catenary curves, log spirals and similar nonlinear forms offering a kind of leverage for his social agency. Even nature could play a role in the exchanges: Bernoulli himself attributes his mathematical interests and style as follows: “Indeed, in the sciences like in nature, there are no leaps, knowledge, like natural quantities grows element by element and progresses only slowly; thus, to pass from one state to the next one, an infinitely small jump so to say, is sufficient” (quoted in Peiffer, 2006, p. 5). The recursive nesting of causal interactions can be extended as far as a researcher has data to support it.

4. The Recursive Mode of Knowledge Flows Part 2: An Indigenous Knowledge Case Study

Adinkra symbols are icons that use geometric abstractions of common objects to convey social or moral concepts. Their stamped image on textiles by the Akan people of Ghana dates back to at least the early 1800s (Willis, 1998), and similar images can be found on brass figures dating back to 1200 AD (Anquandah et al., 2014). After the Asante, an Akan sub-group, fell from power and became part of the British colony of the Gold Coast, nationalist leaders identified the Akan culture, including Adinkra, as a resource to support an indigenous national culture and resist colonial rule (Boateng, 2011). This helped to secure Adinkra as an important part of Ghanaian national identity.

When Adinkra artisans carve stamps to represent animals or plants they often use curves that can be modeled by arcs of logarithmic spirals. One way to think about this relationship is unidirectional: humans simply represent forms they observe. But more insight can be gained investigating it as a recursive relationship, with flows in both directions. Scholars in Science and Technology Studies often describe knowledge as dialectically produced through humans and nonhumans acting and being acted upon by each other (Barad, 2007; Latour, 1987; Pickering, 1995). Accounting for a combination of human and nonhuman agency in the invention of Adinkra stamps is tricky because racist and colonial conventions have been producing portraits of diminished indigenous agency for centuries. To now say: *well the credit does not entirely go to you, we have to credit nature as well,* may seem regressive. However, there are new opportunities for social justice if we pursue this fuller portrait.

Pickering (1995) uses the phrase *capturing nature’s agency* but that may be a more Western conception of human-nature relations. The indigenous relationship is far more collaborative. For example, Figure 5 shows the processing of tree bark (*Bridelia ferrungia*) to create the ink for stamping Adinkra symbols onto cloth. When we interviewed the artisans, they explained that only a small amount of bark is taken from each tree; the bark re-grows and the trees can be repeatedly harvested. Many environments in Ghana are in danger of deforestation, but according to our informants, the areas in which bark is harvested tend to be more protected.

Figure 5. These images show the Adinkra ink production process, from tree, to boiled bark, to Adinkra ink.

We can think of this activity between Adinkra artisans and plants - bark in exchange for protective harvests - as a kind of symbiotic relationship between humans and non-humans. Sustaining this exchange is an indigenous knowledge framework that includes not only ink, but also the symbols themselves. All living things, including the ink trees, are protected by a life force or *sasa*. Rattray (quoted in Adjei, 2010) describes sasa as follows: “Its action is mainly seen among persons who are always taking life such as executioners, hunters, butchers and those who cut down great forest trees. Such persons have to be particularly careful to guard against sasa influence” (p. 13). Unlike the Western emphasis on linear models, many of the Adinkra symbols model nature with nonlinear scaling, which visually implies this dynamic life force. Typically, the nonlinear character of natural structures is represented in Adinkra by logarithmic curves (Eglash, 1999). For example, Sankofa (Figure 6) is the symbol for learning from the past and is represented by a long-necked bird.

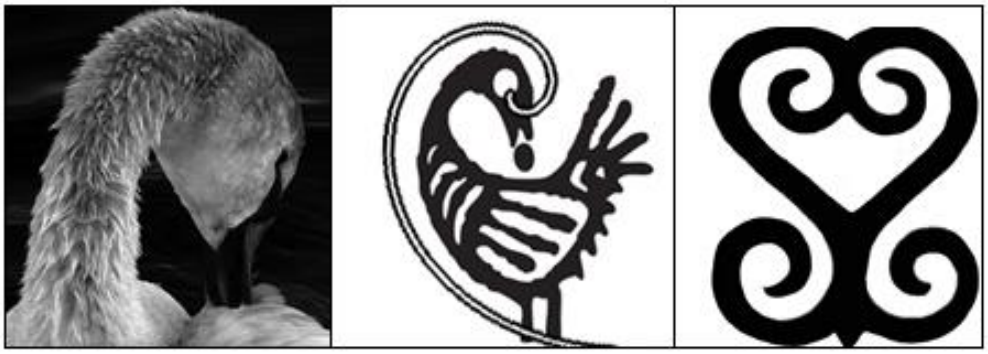

Figure 6. The sankofa symbol: from natural object, to intermediate form, to abstracted form. Source: Frrahm (2011)

The neck of the bird curves behind its body, forming the arc of a logarithmic spiral. We have added a log spiral to the center stamp to show how the shape is associated with the image. At global, national, and local levels, Sankofa is often associated with the activity of looking back towards cultural heritage as a way to move forward (Powell and Temple, 2001).

Other log scaling in Adinkra includes modeling a ram's horn, chicken's foot, and swirls of steam rising from a stew (Figure 7).

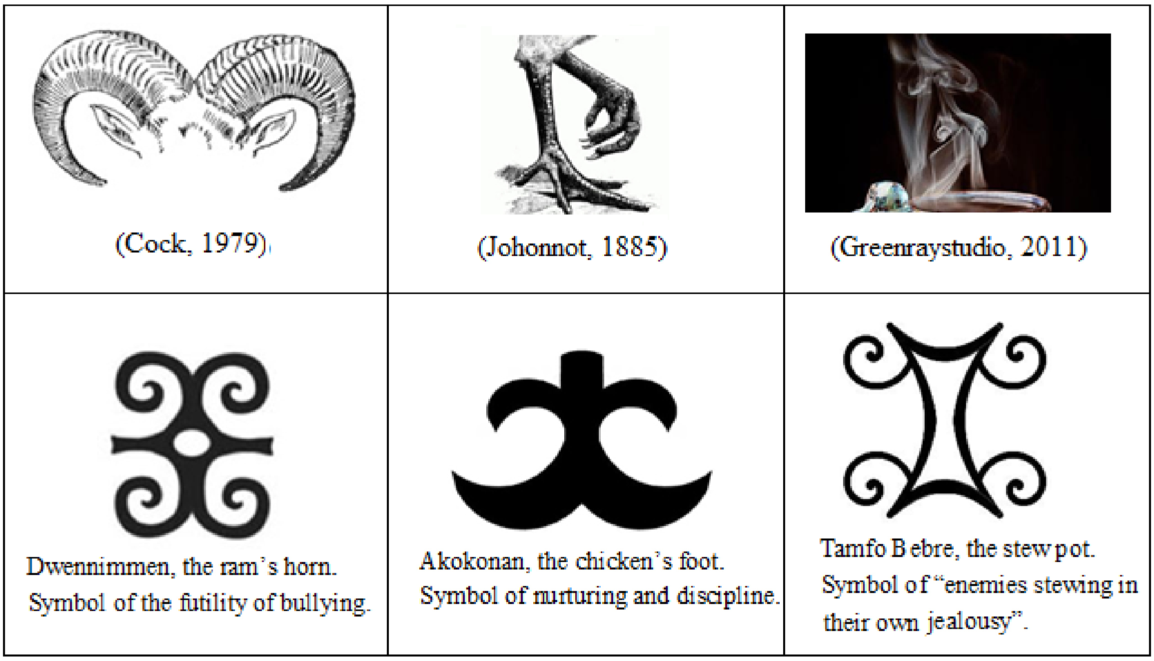

Figure 7. Symbols depicting ram's horn, chicken's foot, and steam rising from liquid

As noted in Eglash (1999) these two categories, living structures and fluid turbulence are the same two categories in which log spirals and other forms of log scaling are commonly applied in contemporary computational modeling. One danger in making these observations is that of mimesis: the criticism that Adinkra artisans are not actually modeling in the intentional sense of a scientist or mathematician, but merely *mimicking* nature. There is an extensive critique of the colonial view of mimicry in postcolonial literature. Bhabha (1994) for example notes that ignoring the indigenous agency in acts of mimicry and assuming natives are merely *aping* what is seen, as if a passive mirror is a classic move by which colonizers primitivized indigenous culture.

As a guard against such misinterpretations, we frame the symmetrical role of humans and nonhumans in modeling Adinkra through the concept of *design agency*. Bennett and Eglash (2013) use design agency to explore how humans and nonhumans come together in indigenous and vernacular design processes. Drawing on Pickering's (1995) concept of *tuning*, they describe the design process as a dance of human and nonhuman agencies; humans are goal-oriented in their design processes but the design must be negotiated within the agential resistances of the material world. This dance is open-ended, in that anything can be changed, techniques, models, methods, or goals--to respond to the resistances of nonhumans to human action.

Evidence for such design agency in Adinkra is extensive. For example, while many symbols model the logarithmic curves of specific organisms, the Gye Nayme symbol uses log curves to generalize the concept of a *life force* as a *common property of all living things* (see Babbitt et al., 2015, p. 118). Far from mere mimicry, Ghanaian Adinkra artists found what scientists would call an *invariant property* - a common pattern underlying the apparent variety of all cases. Another example is the fact that artisans deliberately manipulate spiral properties in coherent ways.

For example, Figure 8 shows log spirals from the ram's horn symbol, Dwennimmen, decorating the chair that was used in the inauguration of Ghana's first president, Kwame Nkrumah. Rather than starting small and expanding, as mimicry would require, they fashioned the spiral to both start and end small, perhaps symbolizing caution against ever-expanding ambitions (which would also fit the Dwennimmen aphorism regarding the moral dangers of being a bully).

Figure 8. Dwennimmen spirals on chair in the Ghanaian National Museum

To summarize: in the previous section we saw that the history of log spirals and their broader family of nonlinear curves in Europe emerged in a context where they were essentially repressed; it took human mavericks like D'Arcy Thompson and non-human agency such as the 1930s Dustbowl to allow their presence. The Ghanaian context had the reverse bias: while many of the linear tools that empowered European math were missing, the alliance between humans and non-humans created both a sustainability that avoided dust bowls and a deep appreciation for nonlinear forms. Figure 9 shows this alternative process of a society in which the recursive nesting of interactions resulted in a more positive appreciation of nonlinear forms.

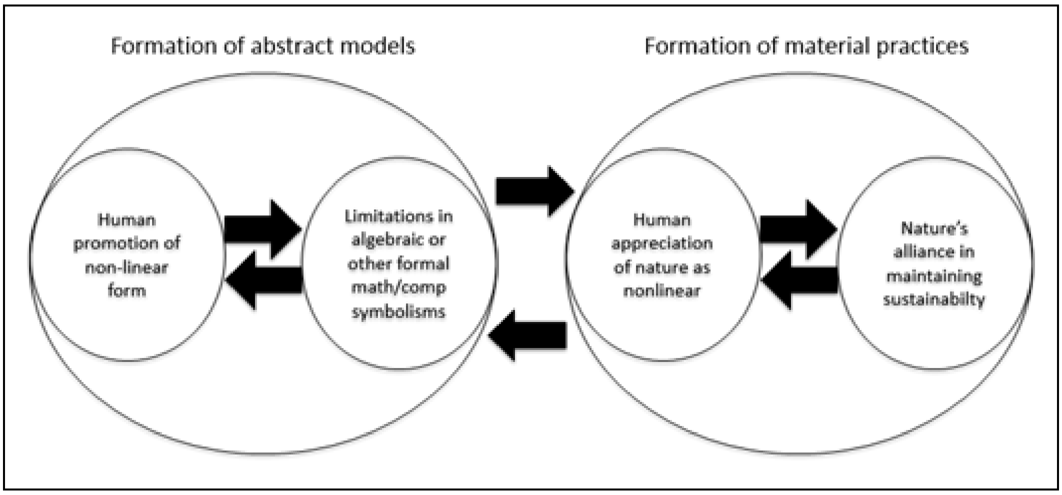

Figure 9. A version of Figure 4, here specific to Ghanaian history

5. The Recursive Mode of Knowledge Flows Part 3: Merging Ghanaian and European Traditions

Today, the Akan people in the Asante Region of Ghana continue traditional uses of Adinkra textiles as funerary arts. Adinkra artisans and communities also make money by selling Adinkra textiles, Calabash gourd stamps, and stamping and weaving experiences to tourists. In competition with these indigenous artisans are mass produced, fake Adinkra cloths that are imported largely from East Asian countries, extracting its value without compensation to local artisans and their communities. Boateng (2011) explores the globalization of Adinkra as a multi-layered site of struggle over authorship, identity, and citizenship that is articulated through contradictions in the applicability of intellectual property laws at global, national, and local levels. Conscious of this potential exploitation, our New York research team took seriously the need to prevent value extraction from Adinkra, and to attempt to replace that with the circulation of unalienated value, as part of the development of educational technology and research programs.

From 2010-2014 we conducted an investigation of the mathematical and computational aspects of Adinkra, including testing the hypothesis that there was intentional modeling of organic growth as a nonlinear form, as well as exploring its applicability to education and development. Our collaborators included an artisan community in the Asante Region of Ghana that made their own ink, stamps and cloth for both traditional uses and tourism. During this time we worked with local Ghanaian teachers to explore various tools within the Culturally Situated Design Tools (CSDT) suite of online applets (Eglash et al. 2006), with particular attention to the Adinkra simulations.

This began with a parametric version coded in Flash (*Adinkra Grapher*) that focused on math education, and then adding a scripting interface (first coded in Java and then Javascript) which would also allow children to learn both math and computer programming (the tool together with its curricular materials we call *Adinkra Computing*, abbreviated here as *AC*). We developed a relationship with two junior high schools (one was across the street from an Adinkra production studio) and one senior high school. We first supplied computers and teacher professional development. These were opportunities to simultaneously conduct research and implement *AC* as part of culturally responsive education with local teachers, students, and community members in and after school. Jorge Appiah's Creativity Group at KNUST continued this work in 2015 by building and distributing Raspberry PI units to allow more classes to utilize the *AC* software.

One goal of this process was to help Ghanaian students make deep connections between math, computing, and their own cultural and environmental heritage. This goal fits within the larger national concerns of many Ghanaian teachers, parents, administrators and policymakers about the underutilization of local cultural resources in primary and secondary curricula, which could be applied to motivate student achievement and connect school content to their everyday lives (Dei, 2004). As we will show below, a recursive approach offers additional opportunities to expand the circulation of these local forms of value through other venues.

In the *AC* interface, users can either simulate individual symbols by creating an algorithm for graphing the correct series of log spiral arcs and other geometric features, or simulate a whole cloth composed of many stamped images by creating an algorithm for positioning and copying. The interface (Figure 10) works by users dragging, dropping, and snapping together *blocks* of code into a script, a coding style developed in MIT's *Scratch* and CMU's *Alice* to eliminate the frustration of typing errors for children. When we attempted to reproduce Adinkra in these other systems, we found that distinct features needed for Adinkra simulations were missing. By adding these features, we hope that *AC* will serve as an example in which indigenous design has contributed to contemporary computing[5].

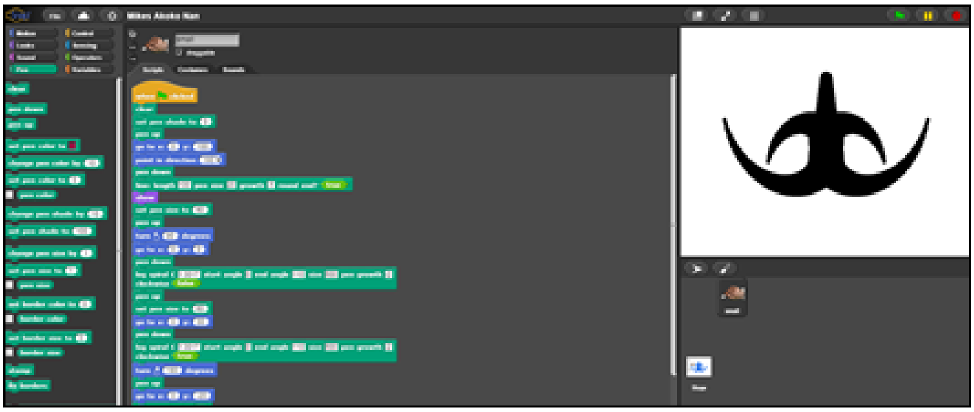

Figure 10. AC user interface

Of particular importance were blocks specially created to facilitate modeling the mathematical operations of logarithmic curves and other graphical elements. Just as the Adinkra designs emerge from emic value-laden negotiations between human and non-human agency, forms of design agency are also at play in the etic modeling of Adinkra symbols for our US software developers. Trade-offs between educational goals, the sociotechnical constraints of the software's many layers (cross-platform issues, processing demands, etc.) and indigenous knowledge are always made. The end result is developed through negotiating these trade-offs in collaboration with developers, educators, and artisans. We aim for each to offer mutual support as part of a larger learning infrastructure that respects the needs, concerns and resources of local communities.

We began by considering the 1D edge of the symbols' curves, modeling them as the arc of a logarithmic spiral. As noted by constructivist learning theory (Harel 1991; Papert 1993; Hutto et al. 2015), having an immediate, concrete visualization in a feedback loop with symbolic manipulation can offer *scaffolding* by which students can move from visual intuition to symbolic math or computing skills. Therefore the notation in the interface had to be made more intuitive than, say, the parametric equations $x(t) = ae^{bt}\cos$ and $y(t) = ae^{bt}\sin$. We started with the equation in polar coordinates, which is usually given as $\text{radius} = ae^{b\theta}$.

However, that form would require teaching middle school children about the constant e, as well as the concept of multiplication of exponents. Another pedagogical issue was helping children with the goal of moving between empirical measures of log spirals in physical natural objects (shells, horns etc.) and their Adinkra counterparts. Placing a protractor against these natural objects, we accomplished this by measuring the radius in a series of angles along the spiral, and plotting the log of the radius against the angles (Figure 11). The slope of the line would then be the constant in the equation $\text{radius} = C^{\theta}$.

[5]Readers can explore *AC* themselves at https://community.csdt.rpi.edu.

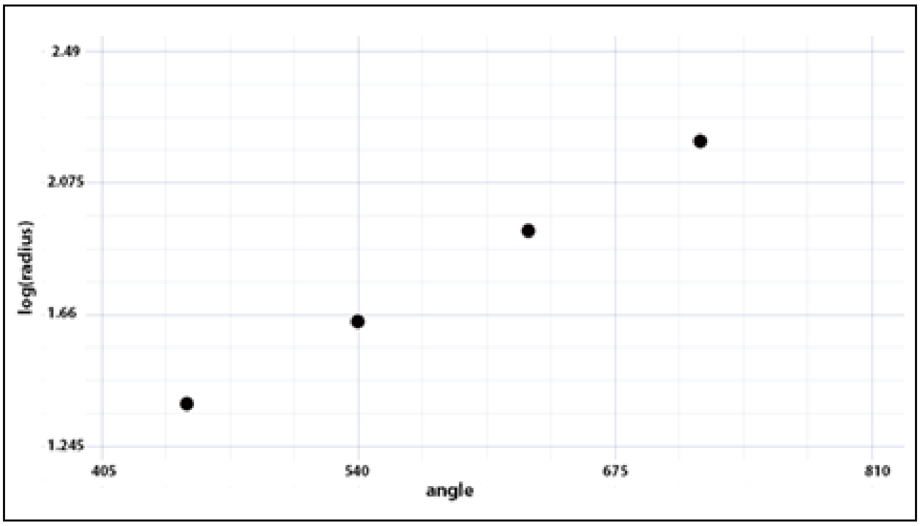

Figure 11. Empirical determination of log spiral curves; the slope provides the constant C for the equation radius = C^{θ}

The equation *radius* = C^{θ} solved several problems at once. It not only allow children to compare a unitary measure of physical log spirals in nature and culture, but also allowed an immediate, intuitive feedback loop in simulations, since changes to the C parameter can be seen on the screen as giving the spiral either a *tighter* or *looser* coil: indeed we came to identify C for ourselves, students, teachers, and other collaborators as the *coilness* of the curve.

This left only a few additional parameters by which these log spiral arcs needed to be characterized. First, the user would need to specify the sweep of angles over which the arc occurs, and the starting place for the sweep. Because *sweep* would then need additional classroom time to be taught, and our experience showed that children generally had a harder time understanding relative displacement than absolute position in simulations, we decided to use *start angle* and *end angle* instead. Since both clockwise and counterclockwise spiral forms can be found in the stamps (as well as in nature) that was also an important function to include. Conceptualizing the 2D character of the spirals was accomplished with *pen growth* — that is, by imagining that a pen was changing size as it drew the line. This slightly contradicts the analogy to carving but as we will show below stamp carvers also start with a sketching process. Finally, we noted that the overall size of the curve often needed to be scaled up or down. Thus, in addition to C there were five other parameters added to the *log spiral* scripting block, as shown in Figure 12.

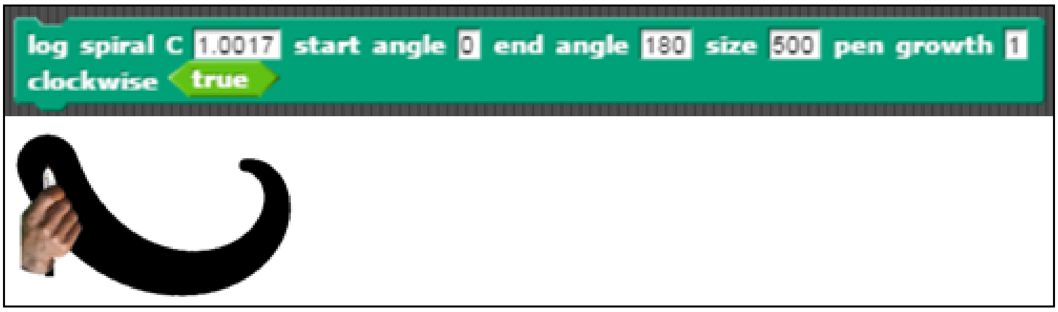

Figure 12. Log spiral block and its resulting log curve

Other considerations included the *object* that was doing the drawing. Again, constructivist theory predicts that children will learn better with concrete physical analogs; in this case we used a photograph of the hand of one of the Adinkra artisans (Paul Boakye) holding his carving tool as he made Adinkra stamps (Figure 12). A harder material such as stone would have to be chiseled at several angles, but the use of a calabash gourd (softened with shea butter) allowed a knife to carve relatively direct paths.

Thanks to these material properties of the natural/cultural object, we found that the line implied by the carving tool edge nicely visualized the concept of tangent and added that to the lesson plan. We also added an option for borders to the stroke, because some stamps such as *Mpatapo* (representing the knot of harmonious reconciliation) required an Eulerian path in which path overlaps could be distinguished from merged paths. Both the fortuitous addition of a tangent line and the deliberate inclusion of Eulerian paths illustrate how the system gradually emerged out of recursive interactions between natural, cultural, computational and pedagogical agencies.

The connections to nonlinear forms in nature also lent itself to additional teaching opportunities in biological sciences. We created simulations in which students could watch single cells multiplying with automated population totals. This offered a context for teaching exponential growth equations. By making a rough approximation that an organism's cellular enclosures (such as chambers of the chambered nautilus, buds on plants, etc.) are roughly proportionate to the number of cell they enclose, students could now relate concepts of cell growth numbers to the *coilness* of logarithmic curves they were measuring: an organism that quickly added chambers to the spiral without much time for enclosure growth would be *tightly* coiled (C approaches 1, the linear spiral). An organism that allows time for enclosures to grow in size before adding new ones would be a *loose* coil (C diverges from 1). Ultimately, we hope to incorporate sustainability lessons with the biology materials.

During the 2014 summer *AC* education research project, we worked with teachers in three different schools in the Asante Region of Ghana. In two of these schools, we had the opportunity to help run professional development workshops that provided a general introduction to *AC* and encouraged brainstorming about implementation. During these workshops teachers worked with computers to develop design agency using the *AC* software. As described by Pickering's (1995) *tuning* concept, teachers learned to use *AC* and model log curves in Adinkra symbols in a *dance of agency* with the computational system. This means that teachers iteratively change strategies, techniques and even their goals throughout modeling processes, sometimes resulting in unexpected creativity when a *workaround* is required.

In a senior high school, we worked with a group of information communication technology (ICT) teachers. In their context, ICT was taught primarily with an emphasis on very basic skills: using a mouse and keyboard, launching an application, etc. Teachers were introduced to the layout of the *AC* interface, provided with supplemental resources for implementation and lesson development on computational thinking, and all engaged in a series of design challenges (*imitate this curve in this symbol*) alongside the *AC* design team.

Gradually the workshop moved from this basic functionality to the incorporation of other kinds of computational thinking: for example controlling the flow of execution with repeat loops or conditionals, changing graphical output with variables, etc. Many of the teachers remarked that this fit within their own pedagogic strategies for students of moving from the *known to unknown*; in this case the *known* was Adinkra and their own ICT curriculum, and the unknown was programming and the *AC* interface. Bringing the known and the unknown together could be described using the bidirectional model; in this case knowledge flow between humans and computers. However, the following description shows that a recursive model can be more illuminating.

During a follow-up visit to the senior high school one teacher decided to create the Adinkra symbol for hope and faith, Onyankopon, which features a cross at the center. To set the x and y starting parameters of the design, the teacher used a *glide __ secs to x, y* block to create the effect of seeing the carving-hand position itself when starting. This choice nicely invoked the feel of watching an Adinkra carver at work, how artisans must be deliberate in movement and positioning. However since this set an absolute position, the *glide* block was not conducive to using a loop to create Onyankopon's cross section in the middle of the circle.

To set a relative position instead, the teacher eventually traded out the *glide__secs to x, y* for a *move steps* block. This may have compromised the ability to convey the impression of a more realistic carving action, but it was efficient at reducing the number of variables required in the script, making it more pedagogically appropriate for her beginning students. At the same time, the presence of the cross at the center invoked a discussion about the use of vertical and horizontal axes of symmetry as part of the indigenous knowledge system. We showed her one of the stamps that had recently been carved (Figure 13) on which one could discern the pencil lines that the artisan had used to mark the intersection of vertical and horizontal lines of symmetry. This helped to provide additional pedagogical strength by which she could describe the software as reflecting indigenous tradition.

Figure 13. An image of Adinkra stamp showing orienting pencil marks left by the artisan

For an outsider who has not observed this process, the final software may appear to be the result of a simple bi-directional path, with culture providing the geometric pattern and Western science providing the simulation. However, the recursive framework is a more accurate description: a series of negotiations between the teacher and the software; each exerting some agency. Looking at the teacher's side, we see further nested flows: decisions resulting from a negotiation between her understanding of the cultural practice and her pedagogical goals. Looking at just the goals side, we see further nested flows; the goals dynamically modified (first capturing the desired continuous movement in the *glide* block; then relinquishing the glide block to gain relative positioning that better fits her student's needs); that modification feeding back into her exploration of the indigenous practice (pencil marks), and so on until the recursion *bottoms out* (Hofstadter 1980).

Perhaps the most profound example of this ethnocomputing approach occurred in a randomized quasi-experiment that compared the effectiveness of *AC* against non-cultural software in a Ghanaian junior high school (Babbitt et al., 2015). In collaboration with a local teacher, we randomly assigned students to control and intervention groups. The control group learned about the mathematics of logarithmic spirals using non-culturally specific software, while the intervention group used *AC* to learn the same math content through the simulation of Adinkra symbols.

Pretest and posttest comparisons between the two groups revealed a statistically significant advantage in the scores of students using *AC*, for comprehension of the material. Rather than locating intellectual achievement and progress elsewhere, *AC* allowed classroom content that was directly relevant to students' everyday lives, encouraging less alienated forms of teaching and learning. This study shows the important role that ethnocomputing can play in education at multiple levels: in the local classroom students learned better through culturally responsive education; the teacher gained a new opportunity for professional development; even the Adinkra artisans benefited by sales of their craft for classroom materials.

Our approach can best be characterized as *generative justice*, an economic framework that attempts to replace the extraction of alienated value with the circulation of unalienated value (http://generativejustice.wikispaces.com/). Principles include a commitment to open-source computing. Open source founders such as Eric Raymond have made explicit the inspiration from indigenous societies, for example in his 1998 essay in a section titled *The Hacker Milieu as Gift Culture* where he notes, "We can observe gift cultures in action among aboriginal cultures living in ecozones with mild climates and abundant food". Thus, we can think of open source as *already* constituting, in recursive fashion, an incorporation of indigenous perspective.

Contemporary indigenous communities with gift economies often co-exist with dominant market arrangements (Ferreira, 2015), but these are often challenged in avoiding exploitative relations. Generative justice provides a framework for facilitating the coupling of gift-economies with other formations (socialist or capitalist). Our first efforts in this direction attempted to facilitate the original alliance between ink trees and Adinkra artisans. Competition from mass-manufactured fake Adinkra cloth has damaged their economy, and deforestation threatens the supply of wood for fires to boil the bark water into ink.

A small grant from the NCIIA enabled experiments with solar production of ink (http://homepages.rpi.edu/~eglash/eglash.dir/susdev/susdev.htm). The next effort consisted of burning the CSDT software to a disk and creating opportunities for software sales to tourists. In this case, we focus more on cloth production than ink stamping, working with kente cloth weavers[6]. Both solar production of ink and sales of simulation software applied *the generative justice* concept of circulating unalienated value rather than extracting it in alienated forms (Eglash and Garvey, 2014).

Having addressed the economic dimensions as best we could, we then set about to reconcile the lack of computers in Ghanaian schools, with the need for computers in ethnocomputing. One approach was termed *Ethnocomputing Unplugged*, after the *Computer Science Unplugged* of Bell et al. (2009). We paid[7] an Adinkra stamp carver to create miniaturized stamps (Figure 14), and purchased a low-cost, diluted form of Adinkra ink from a local ink maker.

Figure 14. Miniaturized stamps

This allowed us to create a computer *output screen* made from paper and to ensure that value flows were enhancing local unalienated production (environmental sustainability of ink trees and the social sustainability of local pride in tradition). We then created a set of physical manipulatives for input (Figure 15), simply taping prints of the virtual blocks to physical plastic blocks (at a total cost of about $3).

Figure 15. Coding blocks as physical manipulatives

Teachers could now demo the software to a classroom using one computer and a low-cost LED projector, and then have each student (or pairs in pair programming (Werner et al., 2006)) create their own code and stamp it on paper (Figure 16).

---

[6]http://csdt.rpi.edu/african/kente/entrep.html.

[7]Gabriel Boakye was skeptical that his brother Paul would be able to carve stamps that small, but Paul's face lit up at the challenge, and he proudly displayed the results the next day; a clear indication that despite the involvement of cash economy, this was unalienated value at its best. A deep examination of the ways that indigenous artists navigate the tensions between tradition, innovation and commodification can be found in Glass (2006).

Figure 16. Miniaturized stamps implementing the physical code block algorithm on paper, using traditional hand-made ink

Teachers could then check to see if the code matched the paper by copying it to their computer (Figure 17). Since the student scripts are usually variations of the demo script, this is not very time-consuming for teachers.

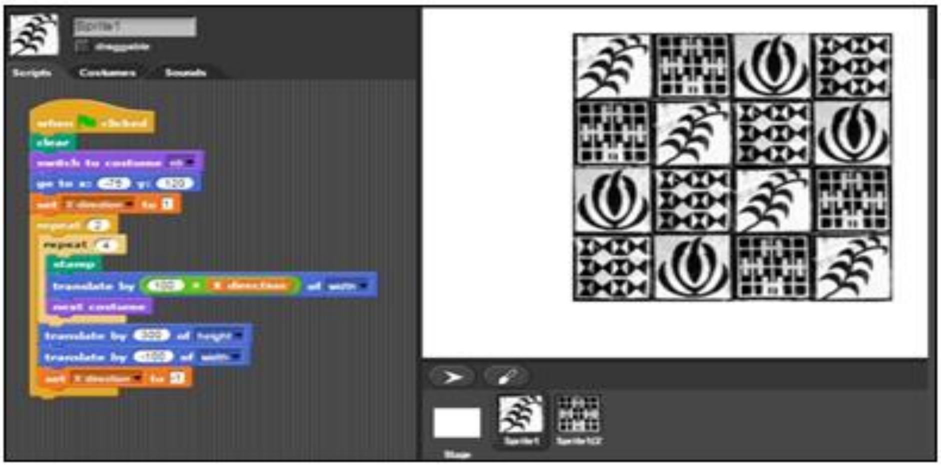

Figure 17. Simulating an Adinkra cloth algorithm

Finally, we also examined the possibility of utilizing cast-off parts from old computers to be recycled into new ones. Accra, the capital city of Ghana, currently has one of the largest e-waste (electronic waste) dumps in the world, and, as a result, toxins from this waste are leaching into the ground water. Working with Jorge Appiah, co-founder of the Creativity Group (an innovation program at KNUST in Ghana), we obtained a small grant from the Raspberry Pi foundation to utilize their low-cost microprocessors together with e-waste components. Appiah's group brought undergraduate engineering students into the participating schools and developed a set of introductory computing lessons, such as teaching about algorithms using the sequence of operations for processing tomatoes into sauce. Their group is preparing the second phase, assembling computing systems from a combination of Raspberry Pi processors and e-waste parts, as this paper is being written.

Since Appiah's Creativity Group was more focused on computer science education, we began a closer examination of etic/emic contrasts in the algorithms for generating whole cloth patterns. A given cloth pattern can be produced by many different algorithms. Rather than view the etic as *more objective* we found that there was an emphasis on minimizing code size for those in computer science (including Ghanaians). That is in part because the culture of computer science was historically affected by the need to minimize code: consider that the entire Apollo Guidance Computer that put the first person on the moon only had 64Kbytes of memory total.

Even today, *bloatware* is a common criticism of software that results in unnecessary delays and resource utilization. In contrast, the culture of Adinkra artisans includes the need to minimize the switching between stamps (to do otherwise takes longer; wastes ink; and increases the possibility of drips). However, implementing these algorithms creates larger code size in the simulations. As Rosa and Orey (2013) note, learning both sides creates a gain in understanding. We hypothesize that this contrast can be used to improve education on the concept of efficiency, as it is rarely taught in terms of something relative to social and material contexts (Farmer, 1994).

The full recursive model for linking indigenous knowledge with Western computing in Figure 19 shows how ethnocomputing can be used to develop mutual enhancement of social justice and sustainability at multiple levels. The innermost level, labeled as interaction between abstract models and material practices, is the outermost level of our previous diagrams (Figures 4 and 9).

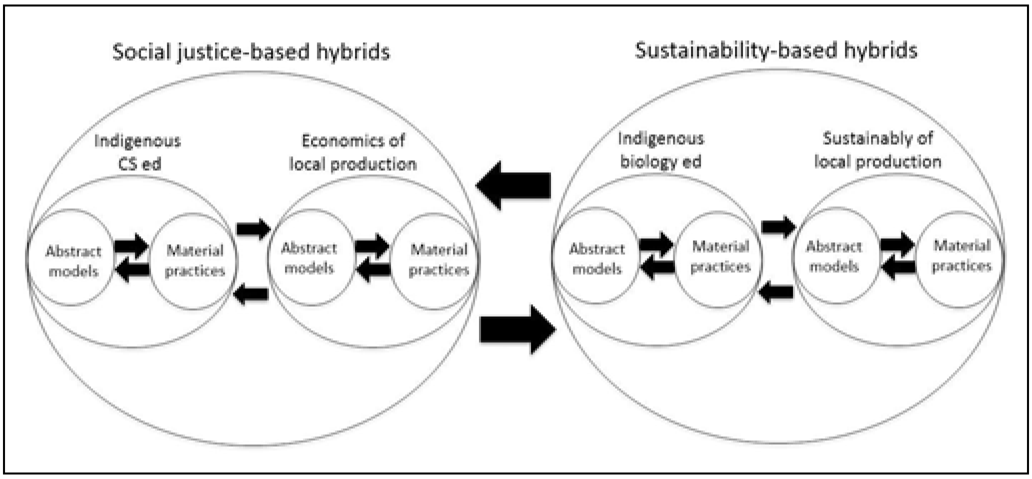

Figure 18. The final model for recursive nesting of agencies in Adinkra computing

As we move out from there, we can see how ethnocomputing might facilitate the circulation of unalienated value from those interactions. If we were to trace, for example, the circulation of value that produces ink in the ideal *AC* system, we would see trees protected by sustainable harvests; ink created from solar heat; regular ink used to produce Adinkra cloth for marketing, diluted ink used in schools for the *unplugged* part of the curriculum; and biology lessons which include the sustainability of ink production. One could similarly trace value flow starting from the computation side: Jorge Appiah’s Creativity Group at KNUST removing toxins from the ecosystem by re-use of trashed computer parts; utilizing these locally-produced computers to leverage the *unplugged* part of the curriculum; the *unplugged* stamps creating market opportunities for indigenous artisans; and their indigenous knowledge providing the computational foundations that aid the development of social justice-based innovation.

6. Conclusion

In this project, our research team used the recursive mode of knowledge flow as a framework for modeling in ethnocomputing. Rather than position emic perspectives as more local and cultural, and etic as more universal and objective, we show that both indigenous and western math/computing concepts arise from recursively-nested interactions of human, natural, and technical agencies, but that they diverge in their emphasis along locally determined pathways.

Taking advantage of this recursive nesting, we then sought ways to intervene in educational practices such that mathematical and computational ideas from indigenous artisanal practices could be brought into activities to support the intellectual development of students and teachers, as well as support the economic and environmental well-being of the indigenous artisans and their communities.

In contrast with projects that extract alienated value, the recursive model promotes *generative justice*, which seeks to maximize circulation of unalienated value: open source software, ecologically sustainable craft materials, and teaching practices such as our *unplugged* CS lessons.

Acknowledgement

The authors would like to acknowledge NSF grants CNS-0634329, CNS-0837564, and DGE-0947980, as well as grants from the NCIIA and the Raspberry PI foundation grant, in support of this work.

7. References

Adjei, J. (2010). *Art and funeral ceremonies in Kumasi.* (Doctoral dissertation). Retrieved from KNUSTSpace (http://hdl.handle.net/123456789/1422).

Anquandah, J., & Kankpeyeng, B. (2015). *Current perspectives in the archaeology of Ghana*. Legon-Accra, Ghana: Sub-Saharan Publishers.

Amoore, L. (2013). *The politics of possibility*: risk and security beyond probability. Durham, NC: Duke University Press.

Ascher, M. (1994). *Ethnomathematics*: a multicultural view of mathematical ideas. Boca Raton, FL: CRC Press.

Babbitt, W., Lachney, M., Bulley, E., & Eglash, R. (2015). Adinkra mathematics: a study of ethnocomputing in Ghana. *Multidisciplinary Journal of Educational Research*, *5*(2), 110-135.

Barad, K. (2007). *Meeting the universe halfway*: quantum physics and the entanglement of matter and meaning. Durham, NC: Duke University Press.

Bell, T., Alexander, J., Freeman, I., & Grimley, M. (2009). Computer science unplugged School students doing real computing without computers. *The New Zealand Journal of Applied Computing and Information Technology*, *13*(1), 20-29.

Bennett, A., & Eglash, R. (2013). CSELF (computer science education from life): broadening participation through design agency. *International Journal of Web-Based Learning and Teaching Technologies, 8*(4), 34-49.

Bhabha, H. K. (1994). *The location of culture*. New York, NY: Routledge.

Boateng, B. (2011). *The copyright thing doesn't work here:* Adinkra and kente cloth and intellectual property in Ghana. Minneapolis, MN: University of Minnesota Press.

Cook, T. A. (1979). *The curves of life: being an account of spiral formations and their application to growth in nature, to science, and to art*: with special reference to the manuscripts of Leonardo da Vinci. New York, NY: Dover Publications.

Dei, G. J. S. (2004). *Schooling and education in Africa*: the case of Ghana. Trenton, NJ: Africa World Press.

Edwards, P. N. (1997). *The closed world*: computers and the politics of discourse in Cold War America. Cambridge, MA: MIT Press.

Eglash, R. (1997). Bamana sand divination: recursion in ethnomathematics. *American Anthropologist*, 99(1), 112-122.

Eglash, R. (1998). Cybernetics and American youth subculture. *Cultural Studies, 12*(3), 382–409.

Eglash, R. (1998). Fractals in African settlement architecture. *Complexity*, *4*(2), 21-29.

Eglash, R. (1999). *African fractals*: modern computing and indigenous design. New Brunswick, NJ: Rutgers University Press.

Eglash, R., Bennett, A., O'Donnell, C., Jennings, S., & Cintorino, M. (2006). Culturally situated design tools: ethnocomputing from field site to classroom. *American Anthropologist*, *108*(2), 347-362.

Eglash, R., & Garvey, C. (2014). Basins of attraction for generative justice. In S. Banerjee, S. S. Ercetin, & A. Tekin (Eds.), *Chaos theory in politics* (pp. 75-88). Dordrecht, The Netherlands: Springer.

Eglash, R., Krishnamoorthy, M., Sanchez, J., & Woodbridge, A. (2011). Fractal simulations of African design in pre-college computing education. *ACM Transactions on Computing Education*, *11*(3), 1-14. Article 17.

Farmer, D. J. (1994). Social construction of concepts: the case of efficiency. *Administrative Theory & Praxis*, 16(2), 254-262.

Ferreira, M. K. L. (2015). *Mapping time, space and the body*: Indigenous knowledge and mathematical thinking in Brazil. Boston, MA: Sense Publishers.

Foucault, M. (2002). *The order of things*: an archaeology of the human sciences. New York, NY: Routledge.

Franks, J. (1989). Review of James Gleick, chaos: making a new science. *Mathematical Intelligener, 11*(1), 65-69.

Frrahm, K. (2011). *Swan clos-up*. Photographer. Retrieved from https://commons.wikimedia.org/wiki/File:Swan_clos-up.jpg.

Gerdes, P. (1999). *Geometry from Africa*: mathematical and educational explorations. Washington, D.C: Mathematical Association of America.

Glass, A. (2006). From Cultural salvage to brokerage: the mythologization of Mungo Martin and the emergence of Northwest Coast Art. *Museum Anthropology, 29*(1), 20-43.

Gosling, J. C. B. (2010). *Plato*: the arguments of the philosophers. New York, NY: Routledge.

Greenraystudio (2011). *Steaming hot mug of coffee*. Photographer. Retrieved from https://commons.wikimedia.org/wiki/File:20110111-_MG_9803-Edit.jpg.

Haraway, D. (1988). Situated knowledges: the science question in feminism and the privilege of partial perspective. *Feminist Studies*, *14*(3), 575-599.

Hargittai, I.; & Pickover, C. (1992). *Spiral symmetry*. Hackensack, NJ: World Scientific.

Harel, I. (1991). *Children designers*: interdisciplinary constructions for learning and knowing mathematics in a computer-rich school. New York, NY: Ablex Publishing.

Hofstadter, D. R. *Gödel, Escher, Bach: an eternal golden braid*. New York, NY: Basic Books, 1999.

Hutto, D. D., Kirchhoff, M. D., & Abrahamson, D. (2015) The Enactive roots of STEM: rethinking educational design in mathematics. *Educational Psychology Review*, *27*(3), 371-389.

Johonnot, J. (1885). *Chicken leg drawing*. (Illustrator). Retrieved from https://commons.wikimedia.org/wiki/File:Chicken_Legs_Drawing.jpg.

Kay, P. (1971). *Explorations in mathematical anthropology*. Cambridge, MA: MIT Press.

Kafai, Y., Searle, K., Martinez, C., & Brayboy, B. (2014). Ethnocomputing with electronic textiles: culturally responsive open design to broaden participation in computing in American Indian youth and communities. In *Proceedings of the 45th ACM technical symposium on computer science education*, Atlanta, GA: ACM.

Koloseike, A. (1974). Models of terraces in Ecuador. In P. A. Ballonoff (Ed.), *Mathematical models of social and cognitive structures* (pp. 28-52). Urbana, IL: University of Illinois Press.

Latour, B. (1987). *Science in action*: how to follow scientists and engineers through society. Cambridge, MA: Harvard University Press.

Maher, N. (2000). Crazy quilt farming on round land: the great depression, the soil conservation service, and the politics of landscape change on the Great Plains during the New Deal era. *The Western Historical Quarterly*, 319-339.

Mandelbrot, B. B. (1983). *The fractal geometry of nature*. New York, NY: W.H. Freeman and Company.

Newell, A. C., & Pennybacker, M. (2013). Fibonacci patterns: common or rare? *Procedia IUTAM*, *9*, 86- 109.

Papert, S. (1993). *The children's machine: Rethinking school in the age of the computer*. New York, NY: Basic Books.

Peiffer, J. (2006). Jacob Bernoulli, teacher and rival of his brother Johann. *Journal Électronique d' Histoire des Probabilités et de la Statistique*, 2(1b), Article 1.

Pennybacker, M., & Alan C. Newell, A. C. (2013). Phyllotaxis pushed pattern-forming fronts, and optimal packing. *Physical Review Letters*, *110*(24), 248-104.

Pickering, A. (1995). *The mangle of practice*: time, agency and science. Chicago, IL: Chicago University Press.

Powell, A. B., & Temple, O. L. (2001). Seeding ethnomathematics with oware: Sankofa. *Teaching Children Mathematics, 7*(6), 369-375.

Quetelet, A. (1835). *Sur l'homme et le développement de ses facultés ou essai de physique sociale*. Paris, France: Bachelier, Imprimeur-Libraire.

Raymond, E. S. (2001). The hacker milieu as gift culture. *Future Positive*. Retrieved from http://futurepositive.synearth.net/gift-economy/.

Rosa, M., & Orey, D. C. (2013). Ethnomodeling as a research theoretical framework on ethnomathematics and mathematical modeling. *Journal of Urban Mathematics Education*, *6*(2), 62-80.

Sojka, W. (2005). *Basler Muenster Bernoulli*. Photographer. Retrieved from https://commons.wikimedia.org/wiki/File:Basler_Muenster_Bernoulli.jpg.

Sutinen, E., & Vesisenaho, M. (2006). Ethnocomputing in Tanzania: design and analysis of a contextualized ICT course. *Research and Practice in Technology Enhanced Learning*, *1*(03), 239- 267.

Tedre, M., & Eglash, R. (2008). Ethnocomputing. In M. Fuller (Eds.), *Software studies*: a lexicon (pp. 92-101). Cambridge, MA: MIT Press.

Tedre, M., Sutinen, E., Kähkönen, E., & Kommers, P. (2006). Ethnocomputing: ICT in cultural and social context. *Communications of the ACM*, *49*(1), 126-130.

West, G. B., Brown, J. H., & Enquist, B. J. (1997). A general model for the origin of allometric scaling laws in biology. *Science, 276*(5309), 122-126.

Willis, W. B. (1998). *The Adinkra dictionary*: a visual primer on the language of Adinkra. Washington, DC: Pyramid Complex.

Werner, L., Hanks, B., & McDowell, C. (2006). Pair programming and gender. In *Encyclopedia of Gender & Information Technology*. Volume 2 (pp. 957-962). Hershey, PA: IGI Global.