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Decolonizing posthumanism: Indigenous material agency in generative STEM

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Abstract

This paper describes a decolonial perspective on material agency in the context of STEM education and application. Using the framework of generative STEM, we engaged in case studies with African, African American, South American, and Native American educational communities. This research shows that understanding material agency based on Indigenous knowledge systems can open a rich source of research and education content. Using a suite of simulations, Culturally Situated Design Tools, we apply this body of research to the classroom. One important theoretical conclusion is the contrast to a "content agnostic" position. A generative framework instead offers a robust blend of user agency and instructional guidance. The outcomes indicate statistically significant and notable improvement for STEM skills and interests. We conclude with a contrast to the quantum epistemology approach to posthumanism. We show that the Indigenous material agency framework in generative STEM is a better fit to decolonial aspirations, and that it offers a more transformative vision for the potential role of STEM in transitioning from an extractive to a generative economy.

Introduction

This paper will describe a decolonial perspective on material agency in the context of STEM education and application. Our empirical work indicates that frameworks for material agency can

Practitioner Notes

What is already known about this topic

- Material agency frameworks can improve our analytic ability to account for real-world phenomena, without reducing everything to a "social text" or semiotics.
- Material agency frameworks rarely focus on the problem of colonial legacies.
- Mediating the legacy of colonization is especially important for education involving those who were colonized (eg, descendents of African and Indigenous peoples). A better way of handling these legacies—a means of decolonizing education—would benefit all students, colonized and colonizer alike.

What this paper adds

- Understanding material agency based on Indigenous knowledge systems can open a rich source of research and education content.
- Research on the use of an Indigenous material agency framework in the classroom allows the use of constructivist strategies without the disadvantage of what we term a content agnostic position. That is, it is offering a combination of user agency and teacher guidance.
- While quantum epistemologies are increasingly popular as a framework for material agency, there are barriers to their application to the decolonial project. This includes the destruction of native lands and peoples in the case of the nuclear industry; the discourse of quantum epistemologies in the performance white people selling faux native spiritualism, and the limitations of quantum metaphors as an investigative framework.

Implications for practice and/or policy

- Combining Indigenous frameworks for material agency with STEM education offers profound possibilities for all students, especially those who are underrepresented.
- Moving between simulations of traditional heritage algorithms and their physical rendering can be a highly effective means to bring Indigenous material agency into classroom methods.
- Using this generative STEM framework, it is possible to enhance the circulation of value between schools and communities, creating a broader transformative vision.

be of strong benefit to education research and practice. But the choice of framework matters. As Rosiek, Snyder, and Pratt (2020) point out, "the engagement of scholars interested in new materialism with the relevant Indigenous studies literature remains an infrequent occurrence." Rather than utilize frameworks from quantum mechanics or similar trends, we propose that Indigenous communities have long held robust, functional concepts and practices for understanding and utilizing collaborative engagements between human and nonhuman material and semiotic agencies. Using the framework of Generative STEM (Bennett, 2016; Eglash *et al.*, 2017; Lachney, Babbitt, Bennett, & Eglash, 2019), we will report on our research developing teaching materials, our development of curricula, and the educational outcomes using this approach. In terms of learning theory, we find a contrast to what we term the "content agnostic" position. Instead, the generative framework offers a combination of user agency and instructional guidance. Our findings show statistically significant increases in STEM interest and performance; better ties to local communities, and a more robust vision for the ways in which Indigenous concepts

of material agency, combined with advanced technologies, can map out potential pathways to a more just and equitable world.

Our first case study provides an example of African concepts of material agency from our fieldwork in Ghana. We will show how the Asante traditionally represented the material agency of plants, animals, minerals and other substances in terms of reciprocal relations with humans. We describe how one set of symbolic forms for this generative economy—the stamped cloth tradition of adinkra—was used in interventions for STEM education for African youth, and its extensions to African American students. We conclude that education theory for generative STEM draws on prior frameworks for constructivist learning, but that it allows for a combination of user agency and teacher guidance.

Our next two case studies examine Indigenous concepts of material agency in North and South America. The South American case involved trickster figures and their relation to biodiversity and other forms of stochastic variation. Our examination of its classroom use is from qualitative data from a teacher professional development workshop in Ecuador. The North American case involved traditions around wood bending, and its integration of geometric, organic, and mechanical properties. The outcomes for this intervention come from informal youth education.

Our conclusion contrasts a more common posthuman framework, that using quantum philosophy, with these Indigenous posthuman materials from generative STEM. We examine the extent to which quantum philosophy has supported New Age trends in the appropriation of Native traditions; the ties between quantum physics applications to Native land theft and destruction, and the limitations of quantum analogies as research in Indigenous knowledge. Thus, we conclude that the generative approach may provide a better fit to the concept of decolonizing education, and more promising contributions to just and sustainable forms of STEM practice and education.

Posthumanist theory: Why Indigenous frameworks matter

Educational inequalities have long been understood as deeply intertwined with broader social justice issues, many originating in the colonial era. Although today best known as a statistician, Francis Galton began his fame as an explorer among "savages" in North and South-West Africa. His 1869 *Hereditary Genius* became a founding text for educational exclusion practices, as well as eugenics (a term he coined), based on his quasi-scientific evidence for statements such as "[t]he average intellectual standard of the negro race is some two grades below our own." Colonial frameworks for genetic determinism were also applied to gender and economic class (Gould, 1981). Restricting the best education for upper class white men turned genetic determinism into self-fulfilling prophecies. Differences in academic achievement could be interpreted as inevitable biology, yet reinforced through social mechanisms: racial segregation, styles of pedagogy, textbook content, and other means of reproducing academic restrictions. To use the title of Fischer *et al*. (2006) it is not inequality by genes, but rather inequality by design.

Galton was not alone. Statistician Pearson (1901) wrote that "the scientific view of a nation is that of an organized whole, kept up to a high pitch of internal efficiency by insuring that its numbers are substantially recruited from the better stocks, and kept up to a high pitch of external efficiency by contest, chiefly by way of war with inferior races" (pp. 43–44). Fisher, Spearman, Terman, Goddard—the list of founding scientists in statistics and psychometrics who were also proponents of eugenics and racial theories of intelligence is daunting. While the scandal of Nazi eugenics paused its march, claims for genetic differences in group mental characteristics re-emerged in new disciplines by the 1970s (evolutionary psychology, sociobiology, neurogenetics, etc.). The postmodernist theories of the 1980s developed in part as a reaction to the ways that science had co-developed inequality by design. If racism was so deeply embedded in science,

then perhaps relegating race itself to a mere "social construction" could be an effective counter. By viewing both humanities and science on the level playing field of rhetoric, they might be reconciled. For example, Richard H. Brown's *Toward a Democratic Science* states this explicitly: "such a synthesizing poetics of truth is the view of science and society as texts." But the phrase "social construction" became so ubiquitous that it lost meaning (Hacking, 1999), and scholars considering the damage caused by "post-truth politics" today often see its origin in these social text theories (Kofman, 2018).

Thus, one can think of posthumanism as having emerged at a moment when reductive forms of science had been shown to be suspect, but its replacement with textual relativism was becoming untenable. It is perhaps no coincidence that two of the most prominent theories, Pickering's *Mangle of Practice* (1995) and Barad's *Meeting the universe halfway* (2007) were both written by physicists. Both understood that postmodernism's relativist tendencies were unnecessary. Once we understand that science can be compatible with the idea that the nonhuman world has a kind of agency to it, we can insist on scientific rigour, while still maintaining, as the progressive motto of the World Social Forum states, that "another world is possible." Pickering stressed the contingency of experiment: scientists are constantly "tuning" the apparatus, theory, goals, and lab configurations in response to Nature's reactions. This back and forth negotiation, the "dance of agency," eventually ends in a place where the scientist can find closure (what Barad would call the agential cut), but other choices might have led to different conclusions.

Both scholars wrestle with the moral implications. Pickering flatly refuses any attempt to see an inherent moral position, stating that any political alliances would emerge from scholars using the mangle framework for a particular political purpose. Conversely, Barad sees the ethical implications as fundamental: individuals are indebted to all Others through an infinite and radically contingent intra-activity. But her critics point out that it is challenging to square this account with the means for systematic social action. Washick, Wingrove, Ferguson, and Bennett (2015), for example, note that in utilizing examples from Leela Fernandes' account of women working in a Calcutta jute mill, Barad emphasizes the infinite possibilities for action, whereas Fernandes points out how diverse actions are nonetheless systematically undermined by forms of race, gender and class domination.

If the goal is to develop posthuman theories of knowledge and practice that address racialized inequalities and related forms of injustice originating from colonial era epistemologies, might there be alternative frameworks from outside the colonial center? Must we be reliant on subatomic physics to reveal other ways of thinking? Or is it possible that Indigenous groups such as Galton's "savages" or Fernandes' lower caste jute workers have their own "funds of knowledge" (González, Moll, & Amanti, 2006) that would constitute a viable framework for nonhuman agency? In the following sections we describe some of our investigations into Indigenous posthumanisms, and the possibilities they engender for educational innovation.

Generative STEM from African concepts of material agency

We typically encounter the history of STEM disciplines as if only one linear progression is possible: in math, for example, we envision climbing from counting to algebra to analytic geometry, calculus, number theory, and so on. But Western disciplines were created in the context of what became economies of value extraction. When we are trying to squeeze as much labor value as possible out of workers in a huge pin factory, or as much ecological value as possible out of an enormous cotton plantation, concepts like optimization or efficiency appear as if they were universal physics (see prior quote from Pearson), and the mathematical, technological and scientific support for value extraction appear to naturally follow. Indigenous economies in contrast are

typically not focused on value extraction; rather they exist to nurture value circulation. Their forms of STEM are created for the *prevention* of value alienation. Indigenous views of material agency, and their equivalent of STEM knowledge and practice, can thus look very different, progress through a different order, and perhaps are even unrecognizable though a Western lens.

Our first examples come from our work in the West African nation of Ghana. Here Indigenous frameworks for nonhuman agency were severely damaged by centuries of colonialism, the slave trade, and the forced imposition of foreign religions. More recently, neo-colonial relations, such as land grabs from overseas corporations, have destroyed enormous spans of tropical forests for planting cacao and palm oil for export. But Indigenous cultures are also sites of resistance, resilience, and resurgence.

One of the locations for resistance has been traditional shrines for the Indigenous animist religions, locally called "fetish shrines" (the Portuguese described African religion as worship of "made objects" or *feitiço*). Colonial Christian zealots systematically destroyed fetish shrines, replaced sacred forests with export plantations, and had their practitioners imprisoned or enslaved.[1] In 1927 Sigmund Freud published his essay on "Fetishism," in which he used African examples to explain his theory of eroticized clothing or other objects as abnormal violations of the natural order, much the way missionaries had done for fetish religion. Just as colonialism enacted forms of violence against fetish religion, neo-colonial policing of sexuality has carried out similar forms of destruction. Right-wing and evangelical movements today have succeeded in making "sexual deviance" a crime in many places in Africa; for example, in Uganda "carnal knowledge against the order of nature" carries a potential penalty of life imprisonment.

Why does the human embrace of agentive material objects cause so much horror and violence in colonial and neo-colonial regimes? To understand this, let us turn to a surviving fetish temple in Ghana, a shrine created by the Asante people in Besease. Using the term "Asante shrine" to avoid the negative connotations of "fetish," Asante, Kquofi, and Larbi (2015) have described the meanings of various symbols. In addition, various members of our team have been working on STEM education from Indigenous knowledge in this region since 1994, along with artisans, elders, teachers and university faculty (Babbitt, Lachney, Bulley, & Eglash, 2015; Bennett, Eglash, Lachney, & Babbitt, 2016; Eglash, 1999; Eglash, Lachney, *et al.*, 2019; Lachney, Bennett, Appiah, & Eglash, 2016). We can begin by describing the symbolism of the stool depicted in Asante shrines (Figure 1). The royal stool was traditionally the most exalted position—Ghana's capital building in Accra is in the shape of a stool—but simultaneously even a poor commoner can offer hospitality with a stool. Asante *et al.* (2015) describe the image of stools on the walls of the shrine as follows:

> The depiction of the adwa (stools) shows that the gnomes are welcome to the temple. For it is only when one is welcome at a place that he is offered a seat. The gnomes help the priest (or priestess) in the performance of their duties. For instance… they might show him a particular plant for preparing medicine to cure diseases (p. 10).

The "gnomes" are a translation of *mmoatia*, tiny forest spirits that create a bridge between human and nonhuman; corporeal and spirit. The traditional relations with nature that were the foundation of Asante life were those of reciprocity between these two realms. Thus, it is no surprise that in some cases the human stool symbol shows a reciprocal relation to the gnome's stool. The power of one stool (nature) emanates from it, forming another stool (human), whose power emanates back to form the first stool (nature). It is recursive, much like the Escher sketch of two hands drawing each other (Figure 2). This is a general representation of how the material agency of plants, animals, minerals and other substances forms reciprocal relations with humans in particular ways in the Asante conceptual and practical framework.

Figure 1: The stool image in an Asante shrine, and a wood stool from the same culture. Shrine image by the author. Stool image courtesy of Deco Art Africa
[Colour figure can be viewed at wileyonlinelibrary.com]

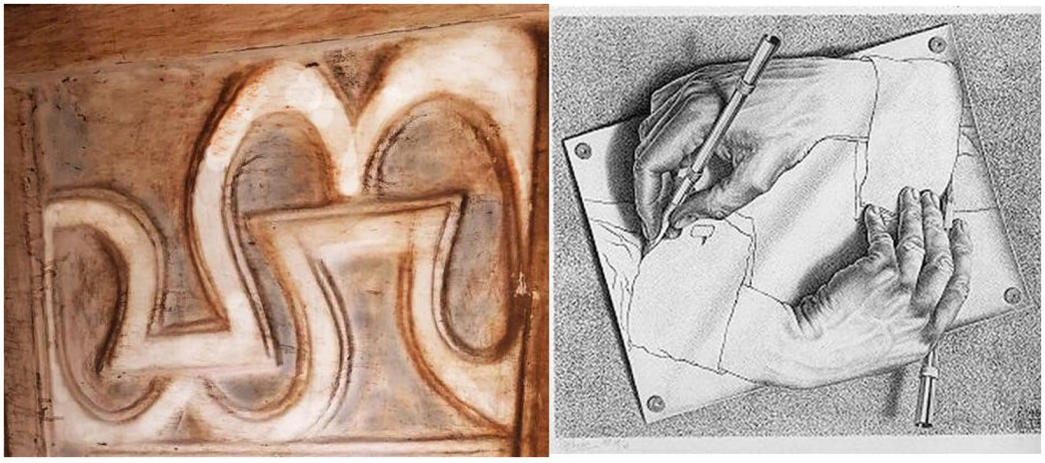

Figure 2: The Asante symbol shows power emanating from nature's stool (upside down) creating the human's stool (right side up), and vice-versa. It is analogous to the reciprocal creation in Escher's famous "drawing hands." Asante symbol photo by the author. M.C. Escher's "Drawing Hands" © 2020 The M.C. Escher Company-The Netherlands. All rights reserved. www.mcescher.com [Colour figure can be viewed at wileyonlinelibrary.com]

We referred to the stool depiction as "symbol" but a better translation might be "flow chart." Figure 3 is an extension of the stool flow chart for the Asante production of adinkra, a stamped cloth tradition. Our information is primarily on the work of adinkra artisans in the town of Ntonso, widely known for this type of handcrafting. Starting in the upper left corner, we see the late Gabriel Boyake, our friend and colleague who sadly passed in 2019, preparing bark from *bridelia ferruginea*, the badie tree. After pounding, the bark is soaked, and the first decoction used as medicine (*aduru*) with significant biomedical properties (Akuodor *et al.*, 2012). Further boiling produces the ink used to stamp cloth with adinkra symbols. Both medicine and ink are available in a "moral economy" that works by a different logic[2] than capitalism's emphasis on extracting value for the highest profit (Mohr, 2013, p. 200). Value that is generated by labor is returned without becoming alienated from those who created it.

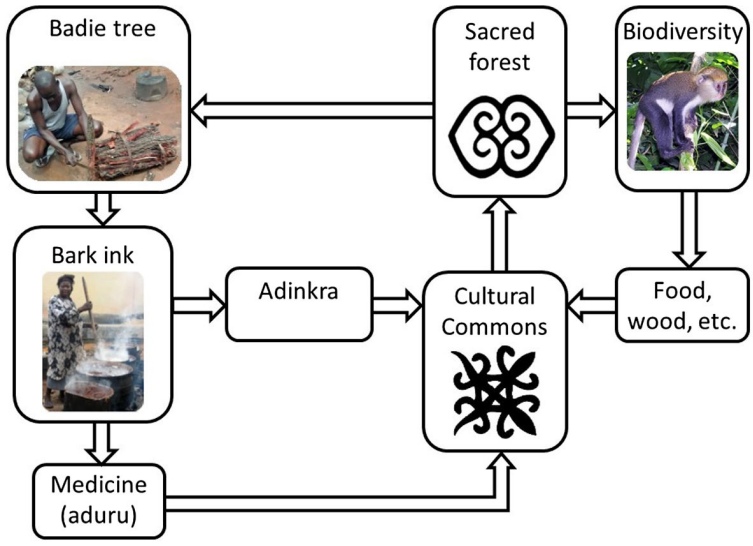

Figure 3: Unalienated value flow in the Adinkra production system. Image created by the author [Colour figure can be viewed at wileyonlinelibrary.com]

Similarly, the bark strained out is not tossed away, but is part of a broad array of strategies for cycling detritus back to nature, including the maintenance of decaying matter in sacred groves. These biodiversity hotspots enrich geographically wider ecosystems; for example, Kankam and Sicotte (2013) show that monkey populations that survive in sacred forests radiate out to other areas. Ultimately this enriches the ecosystems where the badie tree grows, thus completing the cycle. Both labor value and ecological value circulate in unalienated forms. The adinkra symbols themselves are a kind of expressive or semiotic value that also circulates. In the labor commons, we see the adinkra symbol *Funtunfunefu* showing two crocodiles that share the same stomach: "by feeding you I feed myself, so why fight"? In the ecological commons, we see the symbol *Asase Ye Duru* for "earth in balance."

The circulation of unalienated value for labor, ecosystem, and expression comprises *generative justice* as we have defined it elsewhere (Eglash, 2016), and begins to get at the reason why authoritarian systems of extraction find it so repugnant. In Western epistemologies, we have historically approached these concepts strictly in terms of negative feedback: deviance of any kind must be suppressed. But Indigenous epistemologies that bring together human and nonhuman agencies are not monuments to stabilization. In the African traditions, they are sources of fecundity, self-mobilizing and self-modifying. That is why recursive geometric forms (fractals) are so common in African design, and why Europe was so late in its discovery of fractal forms (Eglash, 1999; Lachney *et al.*, 2016; Taylor, 2005). Four hundred years of slavery, colonialism, and extraction economies have taken their toll, but forms of resilience and resurgence can also be found. For example, the first country in the world to constitutionally prohibit discrimination based on sexual orientation was South Africa, and the arguments for that innovation drew on Indigenous traditions that supported human diversity (Murray & Roscoe, 1998).

Generative STEM with adinkra design tools: Classroom experiments

We have been seeking ways to utilize generative justice as the basis for the concept of generative STEM education as well. Just as circulating value between humans and nature keeps the earth in balance, we propose that circulating value between communities and schools allows for less

alienated forms of education. The website we have created for this purpose, Culturally Situated Design Tools (CSDTs, online at https://csdt.org) allows students to investigate the design practices of Indigenous cultures, utilize a blocks-based scripting interface to simulate them, and in some cases physically render their designs using 3D printing, laser etching, etc.

In our test of the adinkra CSDT, we carried out a quasi-experimental controlled study (Babbitt *et al.*, 2015). About 20 Students in a Ghanaian junior high school were randomly assigned to either a control group using a popular educational application (GeoGebra), or an intervention group using the adinkra CSDT site (https://csdt.org/culture/adinkra/index.html). Survey instruments measured both interest in computing careers and knowledge of the math and computing topics covered. The results using a paired *T*-Test showed a significant advantage for the scores for the Adinkra computing based lesson ($M = 45.22$, $SD = 18.67$) in comparison to the GeoGebra computing based lesson ($M = 13.87$, $SD = 15.93$); the difference was statistically significant at the .001 confidence level.

The students using the adinkra CSDT site were able to review the cultural background of adinkra (see above link) as well as scripts for generating its shapes. The cultural background was derived from conversations with artisans and elders, examining the geometric and computational ideas embedded throughout the 60 or so adinkra symbols. As we see in the Asase Ye Duru symbol in Figure 3, log curves are used in adinkra to depict the spiral growth forms found in living structures (animal horns, growing plants, etc.), as well as other kinds of material agency, such as fluid turbulence. In the Asante shrine rituals, paired dancers whirl their hands in opposite directions, performing the paired log spirals associated with Tanu, the river spirit (Figure 4). This reflection symmetry, which we also see in Asase Ye Duru, is just one of the four geometric transformations used in the symbol structures.

After a discovery learning approach in which students were asked to research and present their understandings of the cultural background, they used the scripting interface to simulate adinkra symbols, learning to code the shapes as "heritage algorithms" as well as the underlying mathematics of log spirals and geometric transformations (Figure 5). Readers can examine this curriculum on our website at which is how it was delivered to the students.

Papert (1980) and others have suggested what we term a "content agnostic" position. That is, that students simply program graphics from, as Papert (1980) puts it, "wherever fancy is bred."

Figure 4: Fluid turbulence in NASA computational modeling, Tanu river symbol, and Tanu dance. Fluid turbulence courtesy NASA. Symbol and dance photos by the author
[Colour figure can be viewed at wileyonlinelibrary.com]

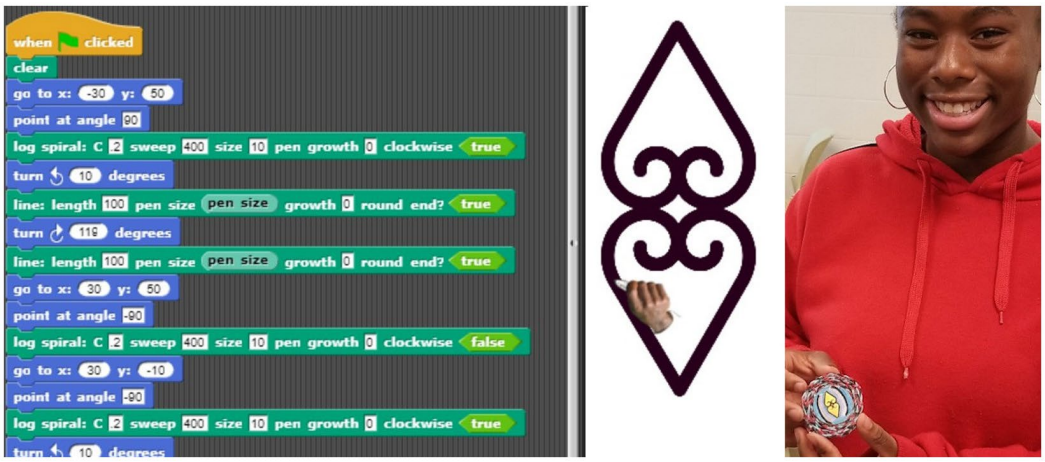

Figure 5: CSDT for adinkra simulations; Detroit student's physical render. Photo by author [Colour figure can be viewed at wileyonlinelibrary.com]

The main representative for that approach today is the Scratch website. The Scratch motto is "we turn youth from consumers into producers." In our examination of content on the Scratch community site (Lachney *et al.*, 2016, para 14) we found:

> 6530 results for McDonalds; 4600 for Disney Princess; 8210 for Transformers; 17 400 results for Call of Duty; and numerous others such as Bratz, American Girl, Strawberry Shortcake, Power Rangers, Care Bears, My Little Pony, Adidas—and let us not overlook over 3 million search hits for Pokemon.

In other words children's lives have been colonized by corporations. A purely "content agnostic" framework is no longer viable, given the commodification of childhood. Moreover, Papert's framework was right in that highlighting the agency of students in creating these designs is paramount (Bennett, 2016). One goal of generative STEM is to move away from the assumption that agency and guidance are diametrically opposed. CSDTs allow design activities to be creative, but simultaneously utilizing heritage algorithms that oppose primitivist stereotypes, and make evident the sophistication of Indigenous concepts and practices.

Similarly, we see our blocks-based scripting interface (Csnap) as combining both Papert's universalized concept of "body syntonic" learning, as well as culture-specific aspects of decolonization. In Papert's framework students would think of themselves as the turtle on the screen. In the adinkra tools they are guiding not a graphics turtle cursor, but rather an image of the carving hand on the screen (a photo of the hand of Paul Boyake, Gabriel's brother). Indeed, students can even be seen positioning their own hands against the screen for angles, reflection symmetries and other calculations.

The photo in Figure 5 shows an African American high school student from Detroit Michigan, who used laser cutting to etch her adinkra CSDT simulation into wood, and then hand-painted and braided a frame for it, bringing the ecology-mind-body flow full circle. In this case we did not run a controlled study, but improvement in pre/post survey contrasts show an increase in STEM interest and skills. Our external evaluators for this project summarized:

> Overall, all participants showed a notable increase in their interest to use and apply patterns associated with mathematics. Students noted that they liked to use math and computers to design patterns. Students also noted that understanding computing would eventually allow them to help their families and that they

recognize that there are sophisticated mathematical and computing patterns present in Indigenous people's knowledge.

Again, there are two parts to the learning theory we invoke here. On the one hand, a content agnostic position can leave commodification forces unchecked. For example, Avle, Hui, Lindtner, and Dillahunt (2019) show how maker exercises can be embedded in regimes where the creation of an "entrepreneurial self" disempowers local communities. On the other hand, there have been studies showing demonstrable advantages in student motivation and learning in the context of physical making (Vongkulluksn, Matewos, Sinatra, & Marsh, 2018). We proposed that the generative STEM framework offers the means to avoid the content agnostic position for makers—it helps to show how the entrepreneurial self is not the only kind of individual you can become—while guiding them toward alternative, more communally oriented possibilities.

Generative STEM as returns of value to the communities of origin

In other exercises with African American students we have focused on cornrow braiding patterns as the CSDT for an embodied heritage algorithm. Students in those exercises explored these patterns in contexts ranging from African traditions, to resistance under enslavement, to AfroFuturist reimaginings. As a means of circulating value back to the community, we also worked with adult braiding shop owners, exploring 3D printing of their CSDT-designed mannequin heads and technologies for measuring and treating hair damage from commercial products (Lachney *et al.*, 2019). Adult learners were especially pointed in their positive comments regarding the value of STEM education that aims to bring the fruits of science and engineering labors to the grass roots and not just corporate bank accounts (Lachney, Babbitt, Bennett, & Egash, 2020).

In the case of both cornrows and adinkra CSDTs, these students and adults showed improvement in pre/post attitudes and/or knowledge of STEM (Babbitt *et al.*, 2015; Eglash & Bennett, 2009). CSDTs include information about the cultural background as well as the simulations. It is critical that students understand, for example, how adinkra artisans came to develop an abstraction around logarithmic spirals through empirical observation and practices in the pre-colonial traditions that developed these heritage algorithms for material agency.

At the university level, undergraduates at Creativity Group (CG: a student-focused organization in Ghana) have collaborated with us, starting with real-time video exchanges with the Detroit students in Figure 5. In summer 2019, we worked with the undergraduates in CG's Kumasi location (Kumasi Hive) to develop experiments aimed to replace the traditional adinkra ink production method with solar-powered equivalents. Again, the standard engineering and business background of these students had emphasized a content agnostic, universalizing perspective: the language of optimization, profit maximization, scaling up. After training with CSDTs, students were better able to describe the need to think about culturally specific aspects of the intervention: How will this impact the gendered division of labor; water collection, the entire network of social ecology? Out of this work we developed an "artisanal cyborg" approach to create human-machine collaborations. This vision for a generative economy would keep labor value, ecological value and expressive value in unalienated forms throughout Ghanaian crafting, such as AI-enabled digital fabrication, sourcing, and authentication that enhances craft upskilling, forest care-taking, and consumer-producer relationships (Eglash, Robert, *et al.*, 2019).

In summary: a persistent theoretical theme has emerged in this work. Standard learning theories, and many of their technical contexts, emphasized a content agnostic position: the world is full of stuff, and our digital technology slices and dices this raw material into whatever we desire. In contrast, our research on the generative economies has taught us that another form of technology is possible. Their worlds are relational, and production happens through collaboration

and negotiation. A generative learning theory is not content agnostic, nor does it impose content from the top down. It is content aware, in the same way that Indigenous communities see an awareness of the non-human material world.

Generative STEM through trickster conceptions of biodiversity: Routes and roots across the Americas

In our conclusion we note the advantages for posthumanism in Indigenous frameworks over the more popular quantum epistemologies. One of the problematic outcomes of quantum epistemologies is the tendency to view all Indigenous cultures as identical "noble savages" whose holistic oneness with nature traps them in a timeless past, erasing specific histories (Wolf, 2010). African and Native American Indigenous cultures have had dramatically different relations between humans and non-humans (Eglash, 2013). As Daniel Heath Justice (Cherokee Nation) summarizes in his review of oral and written Native stories: "Our literatures are just one more vital way that we have countered those forces of erasure and given shape to our own ways of being in the world." The trickster figures in Native American stories are fundamentally stochastic, and form an epistemological network with games of chance, chance-based divination, and maximizing entropy in agricultural practices (Eglash, 2002, 2013). Nature throws floods, droughts, pestilence and other disasters like casting gambling sticks. Only an equally entropic set of genetic resources keeps you prepared. As a result, Native American agroecology deliberately developed an astonishing array of foods that dramatically changed the world, including potatoes, tomatoes, rubber, cinchona (anti-malarial), corn, squash, beans, peanuts, peppers, melons, pineapple, avocado, blueberries, strawberries, tobacco, vanilla, cocoa, and other plants (Eglash, 2016, p. 379).

The localization of anthropological studies to specific geographic areas is not entirely mistaken. Earlier versions of anthropology created primitivist stereotypes by gross generalizations across distinctly different groups. Moreover, postcolonial scholars have pointed out that the mobility of Indigenous peoples and concepts were always very troubling to colonists, and we now recognize the pre-colonial trade routes branching across continents as part of the sophistication contradicting colonial narratives (Beaudry & Parno, 2013). For example, tomatoes were likely first domesticated in Ecuador (Razifard *et al*., 2020), but had already traveled to South Carolina by the time Europeans arrived. Archaeological evidence shows that corn was probably domesticated in southern Mexico about 9000 years ago, but eventually made its way to its northern limits in the Great Lakes region in about AD 1000. There it became part of the "three sisters" agroecology which linked biodiverse growing and nutrient-diverse diets.

Reinhardt (2015) describes how a collaboration between STEM frameworks and this Indigneous biodiversity developed into the "Decolonizing Diet Project" at Northern Michigan University's Center for Native American Studies. With 25 Native and non-Native volunteers adopting a diet ranging from 25% to 100% Indigenous species of plants and animals in the Great Lakes Region, and following an exercise regimen equivalent to a pre-colonial lifestyle, a variety of health and social benefits emerged. Traditional hunting, fishing, and gathering techniques were learned or reinforced; traditional cooking methods found resurgence through potluck, recipe sharing and cooking demos; gains in other Anishinaabe cultural recovery (language, music during potlucks, etc.) were evident, and health monitoring by high-tech methods became more frequent. The improvements in fundamental health indices such as BMI stood in striking contrast to the devastating effects of diabetes and other "diseases of colonization."

Just as the Indigenous stochastic framework can be applied to diet—the relation between trickster's unpredictability and the human maintenance of biodiversity in agroecology and consumption—we have applied it to STEM education using a variety of techniques. In Ecuador we

conducted professional development for math teachers using a Spanish language version of the "woven heaven, tangled earth" CSDT (https://csdt.org/culture/whte/index.html). This tool draws on an indigenous framework in which heavenly grids—the four directions of the cosmos represented in weaving looms, roof lattices, etc.—contrast with the statistical variation of the trickster in creating tangled paths and patterns in the organic complexities of ecosystems (Figure 6).

In workshops with math teachers in Quito and on the Galapagos islands, we explored these heritage algorithms through simulations of South American body painting, pottery, molas and other visualizations of nature's complexity (Figure 6). In the case of the Shipibo designs in Figure 6 they are described as patterns appearing on the cosmic serpent. Sources of these visions for the artists include ayahuasca, a psychotropic tea derived from the *Banisteriopsis caapi* vine. This trinity of growing, making and understanding—the circulation of unalienated ecological value, labor value, and semiotic value—fit well within the generative justice framework. Traditional agroecology of the Amazon—mobile burns for intercropped gardens, composting of charcoal and organic waste to create "tierra prieta" black soil, etc.—enhanced both human and nonhuman biodiversity and sustainability (Heckenberger, Russell, Toney, & Schmidt, 2007; Reyes-García *et al.*, 2008). By what epistemic regimen are these material-semiotic rheological networks created and maintained; and how might understanding this "mangle" (Pickering, 1995) of human and nonhuman agencies help put us on the path toward more generative educational and economic systems?

Anthropologists Kohn (2013), Descola (2014) and others have eloquently described these Amazonian systems in terms of post-human or more-than-human materialities, and the ways that exchanges and syntheses between human and nonhuman collaborators are mutually sustaining. But anthropological voices, even those embracing the new materialism, seem to somehow return to the same old tropes. In his review of a dialog between Descola and STS scholar Bruno Latour, Fischer (2014) notes the persistent contrast: Western ontologies are "machines for multiplying hybrids, while animisms and totemisms are machines for preventing hybrids from

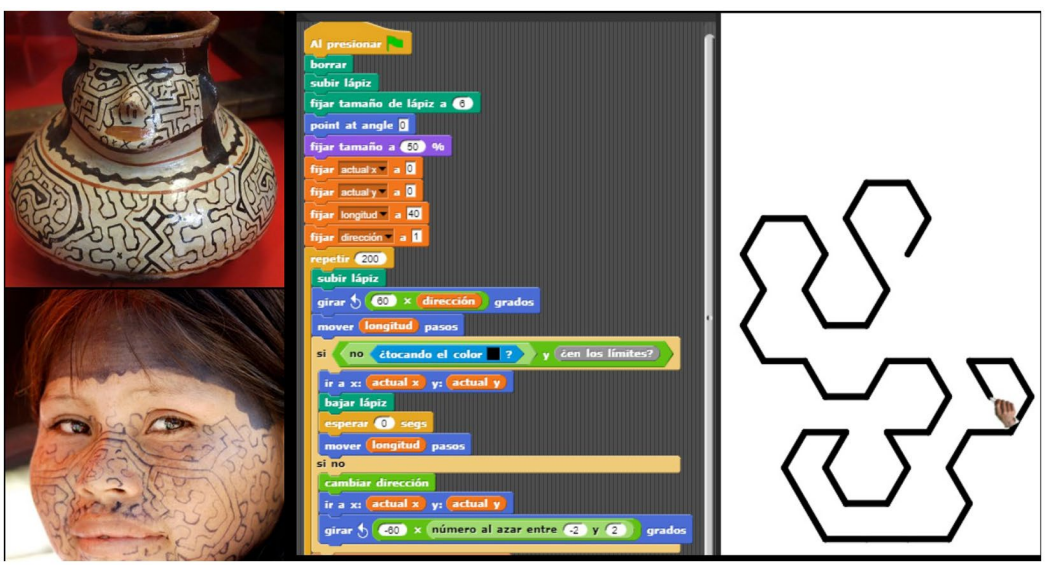

Figure 6: Professional development in Ecuador explored heritage algorithms through simulations of South American pottery and other visualizations of nature's underlying forces of complexity. Pottery image: photo courtesy of Daderot, via Wikimedia Commons. Script and graphic: photo by the author
[Colour figure can be viewed at wileyonlinelibrary.com]

further multiplying." Latour's claim is that science creates innovation because it allows hybridity, whereas Indigenous knowledge is static because animism freezes society in accordance with fixed categories in nature.

As noted previously (Eglash, 1997), Latour is assuming a Western perspective in which nature is static. From an Indigenous perspective nature is full of self-modifying unpredictability. It is the Western view that has, in many ways, based its assumptions on static, linear frameworks: technical obsessions with optimization, linear control, routinization, and so on lead to poor models and practices such as mass production agriculture. And that is why, even today, the plants that were produced over several millennia of trickster-inspired agroecology provide much of the world's dietary biodiversity, where as Europe's monotheism-inspired monocropping continues to be plagued with blights, soil depletion, exploitative labor, pesticide poisoning, contributions to obesity and other disasters (Altieri, 2009; Sentell, 2015).[3]

From that workshop, we found that the Ecuadorian teachers embraced many of these ideas, but also felt the pressures of colonial legacies. Despite some spectacular simulations they created for the trickster paths (including an exercise where they brought in natural and cultural objects to be simulated), teachers overwhelmingly preferred the lattice—in this case the Cartesian-like beadwork CSDT—over the more complex geometries. Since beadwork is common in Ecuador, this was still a reasonable compromise between the pressures to meet conventional education standards and a means to connect the material basis of Indigenous knowledge with its symbolic expression in the classroom (and we did, indeed, find cultural examples of stochastic beadwork where randomness in colors plays a role). But the bead simulations are also nearest to a content agnostic learning medium: in theory any pattern can be made, so the focus on heritage algorithms is quickly lost. One might say that the content agnostic position is a kind of basin of attraction; a gravitational pull away from content aware that is hard to resist, especially in postcolonial contexts.

Generative STEM through wood bending: A case study in Anishinaabe arcs

In the case of North American Indigenous cultures, particularly in the Northeast, lattices often use arcs rather than straight paths. The Anishinaabe Arcs CSDT (https://csdt.org/culture/anishinaabearcs/index.html) allows students to create 3D iterative structures using the heritage algorithms of wigwams, canoe ribs, baskets and other structures. In order to retain the sense of handcrafting, and prevent labor alienation, paper printouts of overhead views of the student-created 3D structures are placed over wood boards. Student drill holes where the virtual structure intersects with a virtual plane, and hand-place reeds. This process of creating a hybrid of human-machine crafting (Figure 7) resulted in both statistically significant improvement for STEM performance and interest. Of 38 students (about half identifying as Native American), the mean on the pre was 3.71, and the post was 11.32. A paired T-Test showed difference in means to be statistically significant with $T = -11.159$, $df = 37$, $p = .000$ (Eglash, Lachney, *et al.*, 2019). Equally important, statements from students indicated this role of material agency was having its intended effect, for example:

> I believe my design represents the two worlds I come from. One being of my Native heritage and the other of the technology era. With the completion of my structure I was able to combine two worlds and accumulate an interest in engineering.… This project has taught me that I can provide and give back for my people while incorporating important traditions and teachings to create a productive environment.

Conclusion

The outcomes of our research with Indigenous communities show a rich set of possibilities for developing translations between Western and Indigenous STEM concepts. They also show that

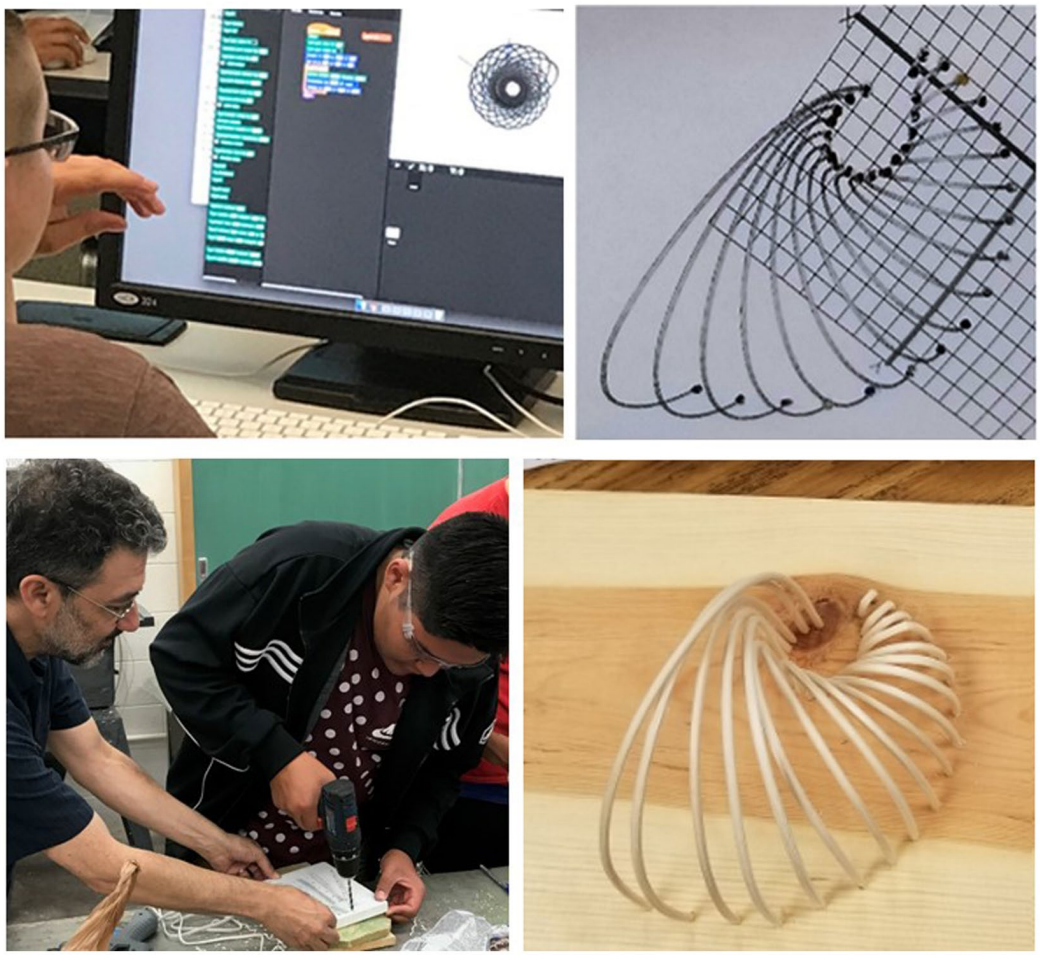

Figure 7: From virtual design, to paper template, to physical rendering with the Anishinaabe Arcs CSDT. Photos by the author
[Colour figure can be viewed at wileyonlinelibrary.com]

Indigenous cultures had utilized concepts of material agency that offered profound forms of support for biodiversity and egalitarian relationships. Finally, we show that utilizing representations of these traditions in secondary education and teacher professional development can show statistically significant and notable improvements in young people (and adult) interest in and/or understanding of STEM and, in the case of students, a strong engagement with teachers. There are also potential contributions for learning theory, as this framework combines user agency with guidance from heritage algorithms. However, a common response to our work is to ask that we translate these material agency theories to the popular frameworks of quantum epistemology. Below we offer some cautions against that translation.

We do not condemn the efforts to utilize quantum physics in metaphorical approaches to understanding nonhuman agency, or applying those frameworks to whatever scholars wish to discuss. But with the power of academic success comes the responsibility to be accountable for its implications. In a discussion of juxtaposing decolonial frameworks from Indigenous scholars (such

as Kawagley (2006) and Smith (2012)) with quantum epistemologies, Patel (2015) suggests "answerability" or Battiste's "response-ability" as strategies in decolonial education. Thus, using Barad's (2007) original framework of feminist conceptions of quantum entanglement, diffraction and so on is not in contradiction with insisting on a social and ethical accounting for the material dimensions of the quantum epistemology framework.

There is a broad precedent for this kind of accountability in education textbook content analysis, where scholars have shown sexist, militarist and ethnocentric bias (Blumberg, 2008; Hill & Robertson, 2009; Hudson, 1987). Uncovering these "invisible barriers" (Blumberg) is crucial to improving education equity. This can also improve understanding in later professional careers. During the Google walkouts of 2018, many software professionals were shocked to hear how their computational technologies would be used for autonomous drone strikes and other military applications (Morris, 2019). Deleterious implications should not be delivered by surprise after one commits to a career.

The utilization of quantum physics in the form of nuclear energy and weapons is well documented; less well known are the ways those practices have been particularly destructive to native communities. For example, in 1946 the US began its nuclear colonization of the Marshall Islands with the detonation of dozens of nuclear bombs on or around the islands, which covered them in significant levels of radioactive fallout. US government documents suggest that officials were well aware of the intergenerational harm they were causing to the Indigenous population (Johnston, 2015) and today the radiation levels are still worse than those of Chernobyl or Fukushima (Abella, Moline, Nikolić-Hughes, Hughes, & Ruderman, 2019). More upstream in the production chain, uranium mining on Navajo lands has also resulted in intergenerational harm. While mining ended in 1986, the Navajo Birth Cohort Study (Shuey, Ong, & Lewis, 2014) shows radiation contamination continues to this day, with increased cancer, kidney failure, developmental disabilities for children, and other health disasters (Lewis *et al.*, 2015). In the case of nuclear energy, the federal "Monitored Retrievable Storage" program from 1987 to 1993 focused almost exclusively on siting nuclear waste dumps on Native lands (NIRS, 2005), and that struggle continues today with Shoshone protests against the Yucca Mountain site (Kuletz, 2004).

At the same time, the quantum metaphor is used by advocates for the New Age movement, such as Deepak Chopra's "Quantum Healing". Since the 1980s, this pseudoscience has fed the emergence of the "plastic shaman": the appropriation of Indigenous culture by White con artists who sell "authentic" spiritual experiences, books, and other faux-native products. For example, Diane Collin's "QuantumThink" (2011) cites a Native American ceremony as the embodiment of her views. Collins was subsequently featured on the "kindred spirits" radio show by Lynn Andrews, whose plastic shaman act has been so offensive that there have been Native community protests at her appearances. As Aldred (2000) explains in the context of North American New Agers, "their fetishization of Native American spirituality not only masks the social oppression of real Indian peoples but also perpetuates it" (p. 330). The appropriation of Indigenous symbolism by such "spiritual hucksters" can be seen as an extension of settler colonialism in which White people claim ownership of lands, resources, and symbolics with little understanding of them or their histories (Churchill, 2003).

At the very least both the technical deployment of quantum physics in Native land destruction, and the metaphorical use in New Age fakery, could be introduced in the uses of quantum epistemologies. Such reforms are common in education fields. We no longer have genetic engineering textbooks without chapters in bioethics, or energy textbooks without chapters on sustainability. Similarly, many US universities now include Indigenous land acknowledgements in their public communications.

But there is one more problem we need to look at: the fact that Indigenous ways of knowing *already* had theories and practices of material agency before European contact. And here is the crucial difference. Substituting metaphors from particle physics for descriptions of actual Indigenous knowledge and practices may drive research away from important sources of knowledge. Research in collaboration with Indigenous communities means you can engage with the actual relations between wood, seeds, dung, and milk; beading, carving, lashing, gathering, hunting, and cooking; drumming, praying, protesting, playing, teaching, and theorizing; in short an entire ecosystem of human and nonhuman interactions richly interwoven with the cosmological theory and practice that make up Indigenous ways of knowing. In contrast, the references to Indigenous knowledge by quantum epistemology advocates are too often a research dead end.

Once you declare that ancient people simply knew quantum truths intuitively through "holistic thinking," what more can be said? And if it is not merely intuition, but rather achievements developed by centuries of hard work from Indigenous thought and practice, then why do we need to replace authentic accounts of that, as we strive to offer in this report, with quantum physics as the explanatory framework? We have shown that detailed computational modeling of Indigenous knowledge can reveal the differences between various Indigenous frameworks and perspectives. In contrast, quantum epistemologies only seem to repeat the trope of "entanglement" or other metaphors, regardless of which context is under analysis (Washick *et al.*, 2015).

Posthumanist thinking and new materialism is much broader than quantum epistemology alone. Many other frameworks abound: Pickering's mangle, Bennett's vitalism, Haraway's naturecultures, and so on. In this paper we endeavored to show that Indigenous ways of knowing can also create more earthly, vibrant possibilities for fleshing out a theory and practice of material agency and its potential roles in just and sustainable futures. One can empower students and communities with contemporary science and technology without adopting a content agnostic position that ignores their histories and identities. Using the generative STEM framework, we can draw on Indigenous knowledge as a basis for understanding material agency, and placing these elements in collaborative engagement with contemporary technological advances in computing, engineering, mathematics and other STEM topics. Once that has been done, a discussion of the destructive effects of the nuclear industry need not be covered up or ignored; in contrast its discussion becomes all the more relevant.

While much of the origins of generative STEM are rooted in Indigenous traditions, the framework is specifically developed for embracing learners of all identities and backgrounds, and we make special efforts to ensure that students from majority positions of race or gender are not reduced to positions of guilt or remorse. We propose that this approach can have immediate and practical benefits to educational practices, school-community relations, and even alternative visions for a generative economy that better provides pathways to a just and sustainable future.

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Statements on open data, ethics, and conflict of interest
The data of this study can be made available upon request.

The Institutional Review Board at the University of Michigan approved this study. Informed consent was obtained from all adult and youth participants and youth guardians. Pseudonyms were used for individuals.

The authors have no conflict of interest.

Notes

[1] This practice continued long after the abolition of slavery. In 1912 the "missionary review" reports "In [Ghana] Christianity has become a real power. The authority of the fetish priests has been destroyed, and heathenism, tho [sic] still fighting and opposing the work of the Christian missionaries, is dying….the development of the cacao plantations… enabled the Christian natives to contribute about $26 000 to the expenses of the [missionary] Basel Society in 1910" (Pierson, 1912, p. 390).

[2] Morh points out that one reason Western medicine was initially rejected was economic: their doctors demanded large payments up front, whereas traditional healers changed a small fee but did not ask for any substantive payment until you were cured, in which case you were merely returning value to the one who generated it. Value returns also work in the negative: the commons for traditional healers is shared risk. Western extractive economies optimize by externalizing costs, so they ensure that all risk falls on the sick.

[3] That is not to say Western history is monolithic: indeed our CSDTs for Celtic history, Appalachian culture and other western variants (eg, https://csdt.org/culture/quilting/index.html; https://csdt.org/culture/systemsscience/index.html) have been created with the goal of engaging all students, white included, in counter-stories for practices of resistance and liberation within Western histories.

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