Variations on a Hexagon: Iterative Design of Interactive Cyberphysical Tokens and Constraints

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ABSTRACT

We describe iterations on the design of a hexagonal token and constraint tangible and cyberphysical interface. Our system has been co-designed both for use in tangible, embedded, embodied interaction and extended reality classroom contexts, and within broader applied generalizations. We survey some of the related literature in hexagonal, rectangular, and triangular tangible interfaces. We express a design space characterizing several aspects of these prior systems; and apply these to a number of additional virtual and physical iterations. We accompany our text with 3D printable, circuit board, and virtual models for a number of these interactors, usable in both tangible and purely virtual forms, including versions engaging four different embedded computing platforms (Raspberry Pi Zero, Raspberry Pi Pico, Adafruit Circuit Playground, and Blinks). We discuss experiences from use of these in classroom settings, and steps toward broader applications.

CCS CONCEPTS

• **Human-centered computing** → *Graphical user interfaces*; *Systems and tools for interaction design*; **Human computer interaction (HCI)**; *Interaction paradigms*; *Graphical user interfaces*;

KEYWORDS

tangible interfaces, cyberphysical interfaces, core tangibles

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1 INTRODUCTION

Many forms of computational systems are internally complex. Simon describes complex systems as "made up of a large number of parts that have many interactions ... [i]n such systems the whole is more than the sum of the parts in the weak but important pragmatic sense that, given the properties of the parts and the laws of their interaction, it is not a trivial matter to infer the properties of the whole." [28, 79] As an example, the "kernel" (innermost core functionality) of the Linux operating system was estimated in 2020 at 27.8 million lines of code [4]. The Microsoft Windows 11 operating system has been estimated at 60-100 million lines of code [80].

Toward assisting undergraduate students in understanding, implementing, and assessing coding aspects of an operating system, one of our departments used an operating systems simulator called OSP (and later, OSP2) [50]. These are divided into a series of modules, all but one of which could be provided to students in compiled form. Students implement and test several modules underlying different operating system behaviors (scheduling, paging, etc.).

This approach struck us as having strong relevance to the tangible, embedded, and embodied interaction (TEI) research community. Garud et al. write "one way to manage complexity is to reduce the number of distinct elements in the system by grouping elements into – and therefore hiding the elements within – a smaller number of subsystems." [28] We find this description strongly resonant with the design and engineering of tangible interfaces, which often require innovations in physical design and fabrication, electronics, computer software, and applied domain content. Here, the modular decomposition described by Simon, Garud, et al. [28, 79] and illustrated by OSP2 [50] could facilitate TEI design and applications both by students and broader audiences of many ages and backgrounds, allowing deeper engagement with one or several implementational aspects, while employing existing patterns for others.

This paper describes iterative design, engineering, and TEI classroom use pursuing such an approach. Specifically, we and our students have investigated many variations on interactive hexagonal tiles, tokens, and tesselations, in both physical, virtual, and cyberphysical forms (Figure 1). We begin by discussing our motivations for the hexagonal shape, and prior work within and outside the TEI community engaging hexagonal interactive elements. We also summarize related work toward other modularized implementations of tangible interfaces and sister approaches. We then introduce a design space for hexagonal cyberphysical interactors; discuss several generations of design and engineering effort; and consider some of the early applications we and our students have pursued, and possible avenues for future research and broader use. We provide open-source (CC BY 4.0, BY-NC 4.0, and LGPL 2.0) versions of several mechatronic and visual aspects.

Figure 1: Overview, hexagonal token and constraint/plinth variations (subset)

2 RELATED WORK

Our most immediate inspirations for investing in hexagonal token & tiling research originated from three sources: Dagstuhl sticky notes, Triangles [31], and digital shadows [39]. At the 2019 Dagstuhl Seminar on Ubiquitous Computing Education, hexagonal sticky notes were provided as a brainstorming resource. The manufacturer began its product description with the bullets:

- A great alternative to the plain square [sticky note]
- Design, facilitate, and run brainstorming exercises
- Cluster&connect ideas with this unique hexagon sticky note

The first of these resonated with a comment by a designer of the Triangles [31] tangible interface, relating to exploration of the design space beyond rectilinear forms. The Triangles system also began to explore labeled edges, but either at a physical distance from screens, or mediated by audio.

We have long found the "digital shadow" notion described within [39] to hold strong potential, but with limited investigation in the literature —- especially for abstract (not intrinsically spatial) associations. The edge-labeling of Triangles – and hexagons – seemed strongly amenable both to proximal-screen and proximal-illumination "digital shadow" augmentation. Extending the hexagonal token vertically (from a several mm thick "tile" to a several cm tall token) provides additional visual and/or tactile real estate for further communicating edge-bindings. The hexagonal shape might stand as a physical and prospectively functionally middle-ground between knob/wheel/dial-like behaviors as illustrated in [19, 20, 46, 47, 85], and block-like behaviors as in [60, 81, 84].

The hexagonal form has received some engagement within the TEI community. Rossmy and Wiethoff's COMB [71, 72] centers on a series of hexagonal tiles, each with six up-facing RGB LEDs, a host microcontroller, and a series of side-facing spring-loaded magnetic electrical interconnects. COMB was described as targeted to "child-oriented musical interaction and education." The hexagons appeared to be roughly 10cm between flat-to-flat sides, and ca. 1-2cm in thickness. We found these to be inspiring and promising, and would likely have built upon their platform if the hardware was available. The tiles each integrated a Teensy-LC processor [1] and (it appears) seven circuit boards. Our investigations sought to realize somewhat simpler, readily reproduced designs, emphasizing labeled printed content on both the surface and faces.

Blinks is a commercial hexagonal tangible interface [11]. Its hexagonal tokens are 3.7cm flat-to-flat, 1.5cm thick. Like Comb, it has six up-facing RGB LEDs, and uses pairs of side-facing rare earth magnets for mechanical interconnect, and side-facing infrared photocouplers for optical interconnect. While designed for intercommunication when directly abutting (and magnetically coupled), the optical communication functions to a spatial offset of ~3mm (important to our investigations; we also understand the hardware has far greater potential range). Extensive software development and simulation resources are provided [9, 10]. We describe one variant of our system that integrates Blinks.

Rooke and Vertegaal's "Physics on Display" used hexagonal tiles as interactors, with projective mediation (presented as a simulation of OLED dynamics) and infrared retroreflector tracking [70]. Samir et al.'s Hexart system developed hexagonal composable multitouch tables, including virtual hexagonal tokens/screen-interactors as application icons [73]. Among many non-hexagonal systems involving compositions of polygonal elements, many systems have explored square or cubical forms (e.g., [3, 26, 59, 60, 84]; and we have discussed Gorbet, Orth, and Ishii's Triangle's system [31].

Beyond the TEI community, there are many histories of hexagonal forms. In the natural world, hexagons are a frequent form, ranging from atomic-scale carbon hexagon rings, to macroscale

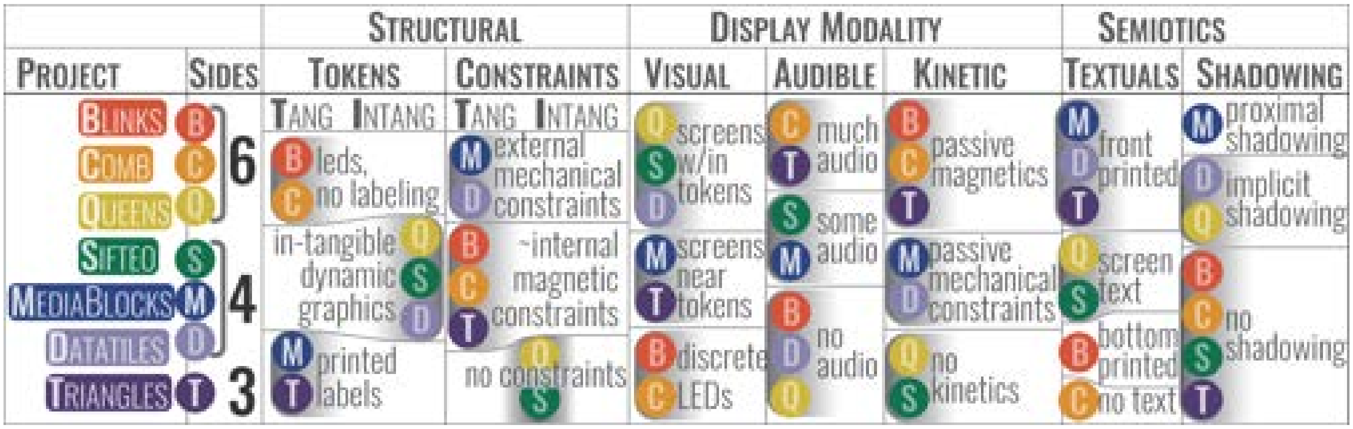

Figure 2: Polygonal token+constraint representational facets: illustration of engagement and clustering among interactive systems' employment of representation and mediation resources. a) seven example systems referenced in Related Work (a subset, chosen through illustration of diverse properties); b) number of polygonal token sides (3, 4, or 6); c) tangible and intangible representational aspects within system tokens; d) tangible and intangible representational aspects within system interaction constraints; e, f, g) visual, audible, and kinetic dynamic display modalities employed within systems; i, j) system engagements with text and shadowing semiotic facets; For (e-i), the upper portion of the regions illustrates relatively "more" engagement; the bottom, no engagement; and the middle positions, moderate engagement. The nodes are structured toward visually clustering similar strategies within each category.

hexagonal basaltic columns (e.g., within the Giant's Causeway of Ireland), to the honeycombs of bees. Archaeologists find indications of hexagonal forms in human art for more than a million years (e.g., [53] p86, per [33]). Hexagonal representations remain common in maps [21], board games [38], architectural patterns [2], urban planning [62], network topologies [66], and antenna [14].

We do not claim that hexagonal tokens are the "best" approach for tangibly representing any particular space of associations. Instead, we feel they offer a sufficiently promising, prospectively generalizable approach so as to be worthy of investigation, investment, and use. We find this particularly so with additional emphasis on mixed physical and virtual labeling (including token top and side faces, and within structuring constraints).

We were motivated by several additional goals. Where (e.g.) the OSP/2 operating system simulator was not intrinsically functional or usable beyond the classroom, we were very interested in working toward elements that – both physically, digitally, conceptually, and pragmatically/functionally – could "scale up" to widespread use. As intensive users of 3D printing, laser cutting, and CNC routing, and (to a lesser extent) a broader span of manual and non-computer controlled electronic technologies (sewing machines, band saws, etc.), we wished to seed approaches that lend themselves to fabrication materials and fabrication approaches, toward providing prospectively interoperable entrypoints for creators with diverse resources, skills, and vantages.

While several tangible interfaces have emphasized reproducibility (e.g., [5, 18, 57, 58]), we wished to target a cyberphysical platform that could span generalizable representation and functionality applicable across a broad range of tangible, extended reality (XR), and broader applications. And in resonance with [82, 83, 87], we sought to create a "core tangible" that could complement diverse "domain tangibles" (e.g., tangible visualizations [82] / data physicalizations [42]) and other computational systems.

3 HEXAGONAL CYBERPHYSICAL TOKEN AND CONSTRAINT DESIGN SPACE

Next, we describe a design space relating to hexagonal tokens and constraints. We can imagine many perspectives on this design space; the below is likely shaped by some of our design perspectives during and following development. We hope and believe it has utility in charting and considering alternatives and tradeoffs between several important shared and differentiating design aspects.

Underlying these, the "token and constraint" interaction paradigm [68, 77, 86] describes how representational and semantic aspects of a system are embodied in a tangible (or cyberphysical) interfaces with different spatial and compositional facets. Rey et al. have charted the properties of between 80 and several hundred such published systems [68]. In this paper, we focus on two aspects: representation and implementation.

While our efforts began and remain rooted in the investigation of tangible interfaces, we have become increasingly interested in a spectrum of systems including cases where most or all interaction elements are virtual in nature. A notable example is the Reactable [47, 48], which achieved success both in tangible and purely screen-based forms. If a system is purely realized onscreen, or in purely virtual form within mixed/extended/virtual/augmented reality environments, it seems curious to describe the system as a "tangible interface." Here, cyberphysical interfaces have been defined as systems designed to work "with and without tangibles, and with and without virtual/'soft' interactors, including combinations of both," with the "choice of interaction modality varying by user, time, and context" [27, 30]. Related applications of the cyberphysical term include [51, 54, 55].

Figure 2 illustrates representational properties of seven systems discussed in Related Work, chosen for their diversity within the space: Blinks [11]; Comb [72]; Queens [70] (as an institutional proxy, given no specific name mentioned for the hexagonal tiles);

Sifteo [60]; MediaBlocks [84]; DataTiles [67]; and Triangles [31]. We are hopeful this representation is both descriptive of the aggregate properties of systems that have motivated this work; and aspirationally generative, in illustrating a palette of more and less explored representational properties that can be employed and proceeded beyon in future systems. Among these representational facets, Figure 2 illustrates:

- **shape:** three (BCU) employ hexagonal tokens; three (SMD), square tokens; and one (T), triangular;
- **structural properties:** relative to our brief consideration of token and constraint systems [68, 77, 86], here we depict the use of tangible (e.g., physical form and/or text) and intangible (e.g., LEDs and screens) representations within tokens and constraints.
  - *tokens:* Blinks and Combs embed six RGB LEDs within each token, but no further visual labeling. USD coincide the tokens with high-resolution pixel graphics (through front-projection, integral displays, and back-projection, respectively). MediaBlocks and Triangles use passive printed materials within tokens to signify digital associations.
  - *constraints:* most of the example tangibles (BCUST) do not engage external constraints, instead compositionally referencing only each other. MediaBlocks (with its "sequencer") uses mechanical constraints adjacent to screens, while DataTiles uses a grid of mechanical constraints on a back-illuminating screen.
- **display modality:** within the example systems, dynamic visual, audible, and kinetic feedback is utilized.
  - *visual:* among the examples, USD integrate dynamic visuals within tokens, and MT within adjacent or proximal screens; while BC use low-resolution (per-face) LED indicators;
  - *audible:* CT make intensive use of audio; SM, modest use; and BUD (to our knowledge), no use.
  - *kinetic:* to our knowledge, none of the seven selected systems engage active kinetic feedback. BCT use magnetic interconnects; MD use mechanically structuring constraints (for M, sometimes together with gravity-assist chutes); and US use passive haptics from token materiality.
- **semiotics:** all of the representational facets engage "signs" and the expression of meaning (semiotics). Here, we summarize two aspects we find of particular import: textuals and shadowing. Peirce's semiotic trichotomy (symbols, icons, and indexicals) is also of strong relevance, including the indexical concept's applications to the presence and configuration of tokens relative to constraints [7, 43, 63], but beyond the scope of this manuscript.
  - *textuals:* for open-ended systems that potentially engage very large information spaces (perhaps resemblant of the Web), text holds a special role for reference and disambiguation. MDT use text (along with other visual forms) printed directly upon the tokens; US use dynamic (screen or projective) text upon tokens; B uses text and icons on the back of tokens (to launch specific applications); and C uses no text.
  - *shadowing:* as earlier referenced, we see special potential in the "digital shadow" notion [39] for hexagonal tokens. Among the example systems, MediaBlocks use digital shadows upon the "sequencer" screen and monitor slot to display evolving block contents and system operations. UD, through their illumination of tiles when upon the interaction surface, can be regarded as employing a somewhat implicit form of digital shadowing. To our understanding, BCST do not employ digital shadows.

We find utility in Figure 2's clustering and illustration of design choices. For example, MediaBlocks and DataTiles cluster with many properties, but not with audio. This could reflect a research-prototype omission (e.g., DataTiles could add audio to supplement its video functionality), but also relates to feedback opportunities. For MediaBlocks use on its "sequencer" and with the "monitor slot" (a constraint affixed to a monitor), the adjacent screens can provide visual feedback. For MediaBlocks, among slots with no internal displays located far away from screens, a visual feedback mechanism was not present, hence the role of audio feedback.

4 ITERATIVE DESIGN AND ENGINEERING

Our development efforts have progressed through several stages. We first introduce these semi-chronologically, and then attempt to characterize some of their properties in the above design space.

4.1 Initial illuminated hextok prototype

Our prototyping of hexagonal tokens (hextoks) began at a Dagstuhl seminar, in a group conversation mapping aspects of ubiquitous computing education. Figure 3a illustrates one such use on an outside table, with hand-annotation on a mixture of hexagonal, elliptical, and rectangular sticky notes. Figure 3b shows a screen or print representation of a refined representation. Here, colors help discern different categories (both at a distance and relative to token edges). Textual and (for the central "perspectives" tile) color were used to label edge semantics.

Participant discussions on fostering ongoing dialogue amongst ourselves, colleagues, students, and broader communities lead us to contemplate prospective roles for tangibles. Figure 3c illustrates a 3D virtual version of the hexagonal ubicomp perspective representations. The gray side-bezel was envisioned as a capacitive touch-sensing element (via carbon-infused 3D print filament [92]), with the surfaces globally or selectively illuminated to represent mixed-initiative human and computational engagement [36].

Figure 3d represents a same-day partially working version of the envisionment. A two-part shell was 3D printed in electrically conductive and non-conductive PLA, and paper and (translucent) vellum labeling was inkjet-printed, trimmed, and glued. A short strip of infacing RGB LED filament was inserted, and linked to an Arduino embedded controller. The 3D print design included a receptacle for a Microsoft Studio Dial. This configuration was linked via plugin to a Unity app, which rotated an associated pixel geometry on the screen when the token was rotated.

Figure 3: Dagstuhl 2019 iterations: a) hexagonal, elliptical, and rectangular sticky notes (with pebble ballast); b) 2D screen representation; c) 3D token envisionment, with partial side labeling (bottom-left); d) first tangible prototype, including internal LED illumination and internal Microsoft Surface Dial rotation+push sensing, with coupled Unity screen mediation.

4.2 Hextok second design iteration

The positive reception by Dagstuhl participants of these prototypes, and their prospects for use both within ubiquitous computing education and in broader generalizations, stimulated us to iterate and further reduce to practice our original design. In this next phase, we made parallel pursuit of virtual and physical prototyping.

Figure 4 illustrates some of the outcomes of this phase. Figure 4a shows a prototypical hextok from this phase. Two length scales have been especially common in tangibles (particularly in rectangular and cubical forms) – 5cm and 10cm, potentially relating to human precision and palmar hand grasp. At Dagstuhl we considered hextoks at the 10cm length scale (as measured particularly between parallel sides, "flat-to-flat"). In our next phase, to economize in space and cost, we pursued 5cm (2 inches) flat-to-flat forms.

With these tokens, we envisioned use as sharing facets of Web pages (including in variety, number, and interlinkage) and parameter wheels [85]. Toward this, we sought sufficient visual and/or physical representational elements upon the hextoks to allow people to identify their digital associations, computer hardware to identify the tokens, and support several types of interactivity. Target interactions included whether a hextok was present or absent in each locality, its identity, and orientation. We were interested in mechanisms to illuminate tokens – as a whole, a particular side or sides, or both – and potentially to allow touch selection of particular sides of the hexagonal tokens. We also sought reproducibility of the tokens, and minimization of cost in both materials, fabrication, and assembly. These aspirations had a number of implications, both for tokens and readers/constraints. These included:

(1) for both the tokens and their readers to be realized with a variety of consumer-grade and larger-volume fabrication processes, and using low-cost, off-the-shelf parts whenever possible;
(2) for the physical tokens to be realizable in a fashion economical both in monetary cost, fabrication time, and assembly time;
(3) for the physical tokens to be readable both with purpose-built tangible interfaces, and with widely-deployed pre-existing technologies (e.g., smartphones); and
(4) for the system to support modes of operation both in the presence and absence of traditional display screens and/or head-mounted displays.

Figure 4 depicts our first full iteration toward these goals. Figure 4a shows a rendering of an assembled hextoken – here, representing six ACM conferences relating to (and including) ACM TEI. An example of the "skin" of this token is shown in Figure 4b, including tabs and holes for fixturing with the upper and lower bezels. Figure 4c depicts both variations of the tokens and an interaction reader/"plinth." Figure 4d illustrate the top labeling for 26 different hextoks. (Side labels for many of these are visible in Figure 7a.)

4.2.1 hextok physical design. To allow hextoks to be low cost, and for their status and use to potentially work without proximal screens, we sought the ability to selectively illuminate the top and sides of tokens. This suggested to us illumination either from the inside (likely with translucent surfaces) or the outside. We also sought to allow different facets of the hextoks (often represented on the sides and edges) to be selectable either by the placement of the tokens; rotation of the tokens; touching the tokens; or touching elements adjacent the tokens (e.g., on the "plinths.")

These alternatives each brought tradeoffs. E.g., for internal illumination, requirements included physical and/or optical access to the inside of the tokens; surface structures that would minimally obscure back-illumination; token skins that would facilitate illumination; and token tagging (e.g., NFC/RFID) selection and placement that would minimally occlude the light.

Our initial approach involved two hextok bezel designs. We initially targeted and tested these with 3D printers, but also chose a design consistent with laser-cutting and CNC milling. Tested 3D printers included the Creality CR10s-Pro and FlashForge Creator Pro (both ~US$800); Ultimaker 3 Extended (~US$5000); and HP JetFusion (~US$300,000)[1]. One bezel integrates a thin printed lattice (to mechanically support a printed overlay and/or NFC/RFID tag, while minimizing optical occlusion, material and energy consumption, and print time); the other is a circular void. Both were designed with 5cm/2in flat-to-flat length. These were printable in ~ 20 minutes/each on the consumer-grade printers, or hundreds of units per night on the JetFusion or comparable printers. (Conveyor belt 3D printers also represent a compelling option, with the number of parts unlimited by bed size.)

[1]In the subsequent text, we sometimes reference present-day pricing. While this is relatively uncommon in academic literature, and some prices (especially of fabrication equipment) will evolve greatly in time, we feel these are important to include. As applied work, oriented both at the classroom and wider world, we find cost to be an essential factor, and one that has substantially impacted all of our design choices.

Figure 4: Second hextok and "plinth" design iteration: a) render of the ACM token; b) expanded view of ACM token; c) physical prototype fabricated by 3D printing; d) top views of additional hextoks.

Several different approaches were explored to fixture these bezels. In the first, we used six button-cap UTS #4 2" long hex-drive stainless-steel bolts, through 1.5"' long 1/4" outer-diameter (OD) nylon spacers, terminated in stainless steel acorn nuts. The screws were initially intended both as capacitive touch points and mechanical fixtures. In initial versions, we planned for the screws to hold down metal touch-pins running along the top or sides of the hextok face. We found this somewhat more complex to realize, and deferred full implementation. The hemispherical acorn nut provided an electrical contact point, and avoided scratching when placed upon sensitive surfaces.

We found that, with our 3D printed design, the spacers allowed the tokens to be structurally rigid. We preferred metric components, but were swayed by cost. With our vendors, 40mm M4 nylon spacers were more than US$3 each; where the similar-length #4 spacers were US$0.35 each. (M4 aluminum spacers were available at US$1.65 each; but this still represented a ~4× increase in price. Naturally, different choices would make sense with varying market constraints; M4 and #4 bolts (as with M2 and #2 bolts) have similar diameters.

In subsequent variations, we found that wooden dowel pins could be a cost and environmentally effective alternative (albeit without the conductive capacitive touch sensing capability, or reusability of the metal screw). A wooden dowel pin had a US$0.04 cent cost per 1.5" long, .25" OD pin: $\frac{1}{8}$ the cost of the spacer, and much less still when the bolt and nut were considered. In many of our designs which do not require in-token capacitive touch sensing, we use three plastic spacers and three wooden dowel pins, as a clamping and alignment mechanism while white glue or Duco cement sets; and then removing the bolts.

We also made numerous iterations on approaches for fixturing and supporting printed labels on the top and sides of the hextok. For the top, if a skin/label were to be permanently attached, adhesive attachment of the label to the 3D print could be an option. Alternately, from reuse, cost, scalability, and environmental perspectives, we were drawn to cases where alternate labels could quickly be "swapped out." There, alternatives we have investigated (applicable to many forms of tangible tokens) include:

- laminated paper (increasing paper rigidity and resilience), including with plastic film, shellac, lacquer, etc.;
- clear acrylic, polycarbonate, or acetate plastic overlays;
- a full ensemble of 6 retaining bolts (to avoid loose corners);
- thin 3D printed borders/mattes/lattices to protect edges and keep printed skins retained; or
- combinations of the above.

Realizing structural support for the hextok sides also presented some design challenges, especially in fashions that preserved optical transparency, and economic (in both time and cost) realization. Options we have investigated include:

- *printed paper, film, or cloth band:* gluing, taping, or laminating together a printed paper, film, or cloth band, with a circumference matching or slightly exceeding the circumference of the hexagonal token, offered one of the simplest alternatives. These could be manually cut (e.g., with scissors or knife), or through computational fabrication tools including vinyl cutters, laser cutters, or routers with dragknife attachments. As challenges, if the resulting label circumference were even slightly greater than the hextok circumference, it would be slack. Conversely, if the label circumference was slightly too small, it would not fit.
- *paper band upon clear strapping tape:* Toward providing side-structure and maximizing optical clarity for internal illumination, we experimented with wrapping the hextok sides with clear strapping tape. This approach was sometimes functional, but marked by several challenges. Getting the tape to properly adhere to small-diameter round fixtured posts was not always easy. The tape gathered fingerprints during application; and the internally-exposed adhesive collected detritus after fabrication. (If internal illumination was not a factor, opaque tape would address some of these.)
- *fused, sewn, or bound plastic or cloth bands:* Another approach investigated involved sewing or heat-fusing cloth or plastic bands as a structural sleeve. We gravitated toward a sleeve-like structure for sewn variants, where (e.g.) a pre-dimensioned canvas ribbon could be flat-sewn at its ends, and then turned inside out. We also tested cutting strips (of varying thickness) of polyethylene film, together with a heated plastic film sealer to fuse a seam. As with the original band approach, the narrow tolerance for length variations was challenging. Promising variations we did not try include a length template jig (e.g., wooden or plastic strip) within the loop to guide binding; or (e.g.) using a vinyl cutter to cut transparent acetate film with holes matching the diameter of minimum-throat-length binding barrels (potentially with a rigid or cushioning washer to ensure tight fit).
- *milled or lased side-panes:* we considered laser-cutting or milling thin side panels, which might fixture within grooves, slots, or joints (e.g., box joint or angular dovetail joint) with the top and bottom bezels. If made with clear or translucent materials (e.g., lased acrylic or milled polycarbonate), these could support internal illumination.
- *dimensional 3D print or cut form:* if a 3D printer is available, the simplest option might be printing of a shell in final form. This could either be self-structuring (with walls sufficiently thick to maintain structure), or dependent upon the scaffolding structure of the above-described pins and spacers. Optical properties are also a consideration, with (e.g.) ~clear PETG providing good structure, abundant recyling sources, and optical diffusion. We picture two such variations, and provide their printable STL files (CC-BY).
- *flat 3D print:* we considered 3D printing thin, flat PLA, PETG, or nylon sidewalls, coupled with bolts or binding barrels. With the flexibility of these materials (when thin), the sidewalls could be fixtured in tension against the above-described spacers, pins, pegs, sparser dimensional 3D prints, etc.
- *panelized 3D print:* pins, nails, wires, etc. can be used as pivots and joins linking a plurality of side panels. This approach has lower material costs than a screw; reduces printing time through the smaller diameter cavity; and allows selective repair and replacement or recomposition of panels.

4.2.2 hextok plinth design. Conceptually and pragmatically interwoven with the fabrication of hextoks (or any other tangible token) lies the challenge of token recognition, mediation, and (for token and constraint approaches) the physical expression of semantics. We long debated naming. In resonance with [68, 77, 86], "constraint" would be one candidate, but that term is somewhat abstract, and arguably without intrinsic expression of the semantics that we sought. For example, the natural course of a river or mountain forms constraints; but not ones intrinsically codifying a synthetic semantic language. Other candidates included "cell" or "pad," as within [84]; or reader, per the common underlying tag functionality.

As an alternative, we were drawn to the architectural concept of the "plinth." Glaser et al. write "the English word 'plinth' is the base or socle upon which a column, statue or structure rests.... According to the German architect Gottfried Semper (1803-1879) the plinth exists to negotiate between a structure and the ground (The Four Elements of Architecture, 1851)" [29]. Semper's German expression of the four fundamental elements of architecture [74] (page 55) – *Herd, Dach, Umfriedigung,* and *Erdaufwurf* has been variously translated; among these *hearth, roof, walls,* and *plinth* [29, 65].[2]

Our first plinth is pictured in Figure 5. As shown, it incorporates an Adafruit Circuit Playground processor board (round, 50.6mm/2" OD); a Raspberry Pi Zero W; two or three NTAG NFC readers; a length of RGB LED strip; one or several capacitive sensing boards; a Hall effect magnetic sensor, and an inductive power coupler. It also includes 6 copper lugs; 6-8 zinc-plated steel dowel pins; several bolts; and optionally, several functional touch washers.

The Playground board integrated 7 capacitive touch sensors and 10 RGB LEDs on its face. We connected 6 touch sensor pads to the copper lugs, placing their open holes beneath the six bolts and acorn nuts at the hextok corners (Figure 5a and b, top-center). These allowed the rounded button cap bolts atop the hextoks to electro-capacitively couple to the Playground, acting as touch-sensors; while also allowing the copper lugs to serve the same function.

The hex plinth's six sides had several functional and representational properties. Figure 5a top-left illustrates how the sides extend ~0.5" above the hextok's baseline. This approach served both NFC sensing and LED illuminative roles. We found that if placed directly beneath the Playground, NFC boards were masked and rendered non-functional by the Playground's circuit board (perhaps

[2]Semper imbued these with social and even moral aspects. For instance, these included symbolic representation of family associated with the hearth [74, 75]. He also deeply engaged with the colorations of Greek and Roman marble architecture, and the weaving of first peoples wicker and rugs analogous to the development of stone walls. In Brand [13] and Rodden and Benford [69], we see compelling prospects for these ideas relative to cyberphysical applications – e.g., analogs between the hearth and computation. We have also found examples like London's Fourth Plinth to be relevant, evocative, and aspirational [89].

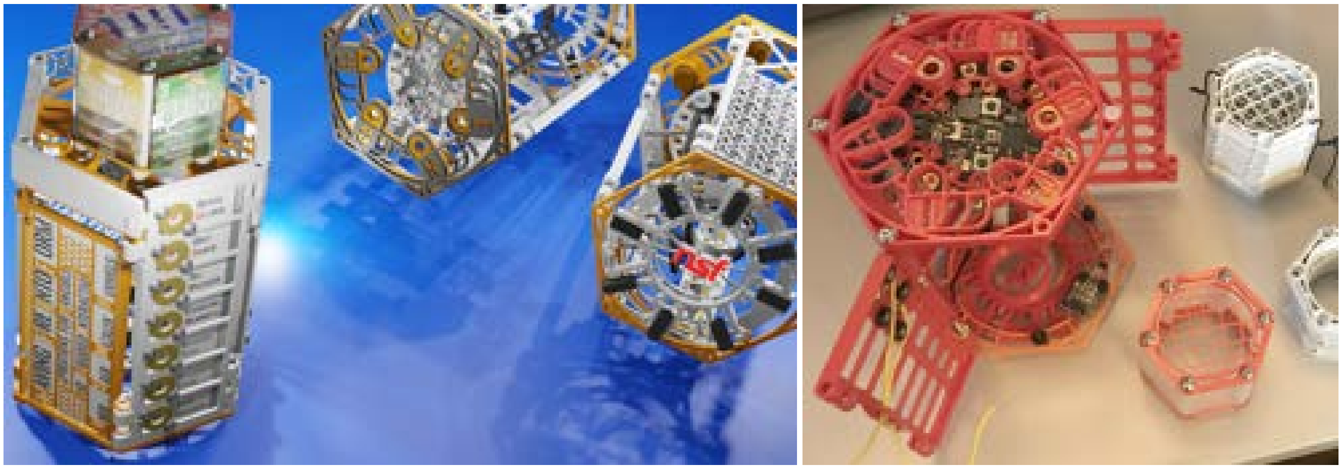

Figure 5: First full plinth iteration: a) virtual (Blender) views of sides, top, and bottom of plinth; b) view of 3D printed assembled plinth prototype, including visibility of internals.

incorporating a ground plane) and components. Conversely, if the NFC boards were placed atop the Playground, many of its LEDs would have been obscured. As a workaround, we integrated two NFC NTAG 213 tags (today typically ~US$0.25 each in several-unit quantities, and interoperable with many iOS and Android mobile devices) in the bottom of the hextok, parallel with the sides; and three NFC readers (of a kind typically ~US$3 each) within the top of every second hex plinth side panel. This provided just enough range and overlap to sense the hextok's identity and orientation. The overlap also provided space for a side-infacing 14mm wide RGB LED strip to illuminate the hextok's sides, or for reflectors or transparent acrylic spheres (acting as ball lenses) to redirect the Playground's LEDs for selective hextok side-illumination.

We controlled the Playground and NFC boards from a Raspberry Pi Zero W, with wifi capabilities allowing bridging to external Internet-linked devices and the cloud. The Pi and NFC boards were bolted flat against a side of the hex plinth. The length of these circuit boards suggested a substantial plinth height/depth, which we sometimes regarded as an opportunity. Partly to apply this 3D real-estate in fashions not easily approximated with a 2D screen, we attached capacitively-sensed, RGB strip-illuminated washers and visual labeling to some of the faces; and passive physical labeling on other faces. We used a pattern from the ceiling of the Whistler and Jeckyll's Peacock Room [90] as an aesthetic structural lattice.

We explored both battery, power plug, and inductive power approaches for powering the plinth, finding each attractive and relevant under different usage contexts. Especially for the inductive power case, we explored an approach where one or several magnets could be placed within the source inductive power's chassis. These could mechanically couple to the $\frac{1}{4}$" OD steel dowel pins, while their magnetic field could be sensed by the Hall effect magnetic sensor.

3D printable STL files for the pictured plinth are provided CC-BY-NC 4.0.

4.3 Student variations and actuated table

We have used hextoks and plinths in three TEI classes, allowing students to employ virtual or physical hextoks, or self-made TEI variants. When hextoks and plinths alone were provided as resources, about half of student teams chose their use throughout the semester. When three alternate platforms were provided, roughly a third of teams chose hextoks and plinths. In these uses, students focused efforts in different fashions. Some focused on the physical fabrication of hextoks and/or plinths, sometimes in diverse materials (e.g., solid 3D prints, wooden popsicle sticks surfaced sides, containing soil, etc.); sometimes focusing on embedded processor programming or smartphone use. Many students put QR codes on the sides; others proposed LCD or OLED screens on one or all sides.

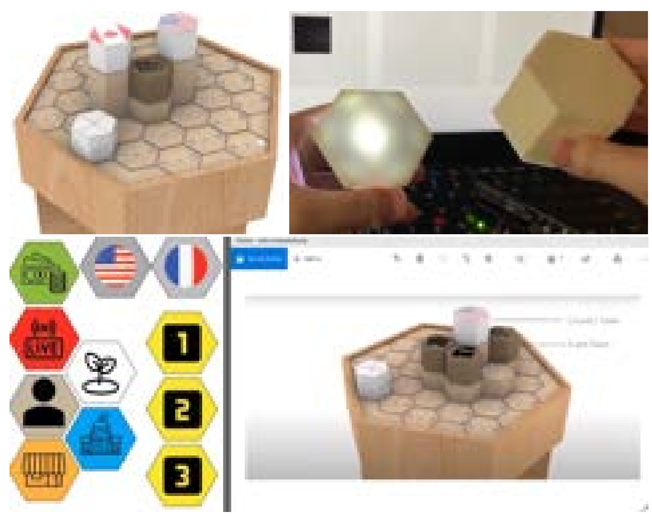

Figure 6: Stills from animation of actuated hex table (student class project)

One student project particularly inflected our work. Figure 6 illustrates an actuated table choreographing movement of several interacting hextoks. Computer animations illustrated how these could be employed in several interaction scenarios involving the United Nations Sustainable Development Goals (SDGs).

Figure 7: Actuated hex table variations.

These lead to an extended collaboration on possible actuated hextok table variations. Several of these are visible in Figure 7. In 7a, a single hextok plinth is surrounded by 18 distinct hextoks (with populated hextok side panels also visible). Here, we anticipated employing actuated sensing and illumination [88], with two or 2N NFC readers and RGB LEDs rotated beneath the hextoks, toward reducing system cost and enhancing scalability. (If coupled with additional magnetic, etc. sensors, operating system disk scheduling algorithms could be evolved to optimize seek performance [44].) An LCD or e-paper display on the table's front-left could provide additional assistive and mediative information.

Figure 7b and c illustrate an ensemble of vertically-actuated hextok plinths. As illustrated, each plinth might have two small displays (here, sized to commercially-available 1" diagonal e-paper or OLED displays), with three somewhat larger bicolor e-paper displays mediating additional subregions of the space. Figure 7d shows both variants integrated within a larger subtable. In addition, the right-center illustrates a potentially actuated rack of collapsed hextok skins; and the bottom-left, three hextok plinths in a multitouch tablet context (subsequently described).

4.4 Reduced complexity, lower profile, rotationally actuated hex plinths

We found many aspects of our initial plinth design to be promising. Simultaneously, for some of our classroom use cases, the design had more cost, complexity, and 3D print time than desired. For these reasons, before fully fleshing out the design's software, we decided both to pursue additional prospective use cases and contexts and a more compact design. The latter also resonated with the architectural distinction between two common plinth variants: pedestals and socle, the latter typically being shorter in stature.

We prototyped several subsequent generations of hex plinths and hexmaps through this approach (Figure 8). We initially deferred orientation and capacitive touch sensing, focusing upon NFC sensing and illumination. We discovered that the Raspberry Pi Zero and NFC boards could be fixtured in parallel with several millimeters offset at a 60 degree angle, with each retaining full functionality.

Figures 8a-e illustrate virtual and physical prototypes of these lower-profile plinth variations. These lead both to unanticipated properties supporting interaction with hexmaps (discussed in the next section), as well as several challenges. First, most Raspberry Pi boards left the marketplace for non-commercial purchase for roughly three years during the COVID-19 pandemic. We were uncertain whether it was wise to invest deeply in software and hardware optimized around a board that might not have accessibility to the builder community. Second, our Blender point light source simulations left us uncertain regarding functional approaches for directing unlensed side-facing LED ribbons up across the sides of the hextokens. Combined with the Raspberry Pi availability concern, and the unresolved aspects of token orientation and touch sensing, we transitioned to development of two alternate prototypes.

Figure 8f depicts the first of these. Here, wooden popsicle sticks were planned for horizontal structural elements, with 3D prints and nylon spacers fixturing these at the corners. A three-winged NFC reader geometry would detect token position and orientation with two NFC tags just below (and parallel with) opposite hexagonal token side-surfaces. We experimented with both paper and cloth suspensions between the popsicle frame and hextok, to redirect outward side-oriented RGB LED strip illumination back toward the hextok, and to provide a visible indicator of active hextok faces, even on the faces oriented away from the viewer (as another kind of digital shadow).

Figure 8g-j shows our most recent plinth variation. First, we observed that a ~US$3 microservo could rotate a hextok upon a 3D printed geared support. In the context of "ghostly presence" [39], coupling hextok rotation to the manipulations of remote people or digital sources, we felt this could majorly impact the system's perception. We identified an approach where a single off-center ceramic magnet and a high-dynamic range magnetometer could sense

Figure 8: Lower profile hex plinth variations: a) assembled 3D printed assembly for first lower-profile plinth. b) partially assembled version, showing female-male jumper assembly of two NFC boards and a Raspberry Pi Pico through a mini solderless breadboard. c) closeup of labeled mini solderless breadboard. e) 3D view of refined version, including embedded bicolor e-paper display. f) plinth variation incorporating representation of antique handcuff, including with integrated mini-display and speakers, in context of slavery and its legacies; g) plinth variation with popsicle sticks as primary structural member, including three NFC-reader ensemble for detecting two-tag token presence, identity, and rotation. h) closeup of circuit board fabrication for g, but with single NFC reader in flat configuration together with Raspberry Pi Pico embedded controller. i) variation including saddle washer light-shapers and touchpoints and rotary servo actuation. j) alternate view of (i), with transparency toward visibility of more internal components (e.g., round plated steel magnetically coupling strike plates on 3d printed, micro-servo actuated gear (orange). k) internal fisheye view of (i-j), with upper orange gear, right purple micro-servo, 3D printed internal scaffolding visible.

the orientation of a hextok, allowing a single bottom-surface NFC tag to provide identity. This same magnet could loosely couple with an array of plated steel "strike plates" (Figure 8i, silver discs), facilitating the servo-driven actuation. Curved "saddle washers" served both as optical reflectors, and capacitively-sensed touchpoints.

Partly on the basis of availability, lower cost, and higher embedded-support functionality, first versions of the most recent two plinths are based upon the Raspberry Pi Pico RP2040 processor. This plinth requires parallel monitoring and control of five channels: NFC, capacitive sensing, magnetometer, microservo, and addressable RGB LED, along with native behaviors. Toward this, we initially based implementation in Arduino/C++ rather than Python, in what begins to approximate a simple operating system. (This is assisted by the RP2040's dual compute cores, with hardware interactions serviced on one core, leaving the other core to mediate interactivity.)

We found anecdotal reports of successful SPI Pico support (necessary for hardware-assisted parallel processing of NFC reader updates). We have not identified confirmed public RP2040 SPI hardware-assisted code, and continue local implementation. The MBED RTOS RP2040 Arduino flavor compiles substantially (near order-magnitude) more slowly than for AVR processors (possibly because of OS integration), which also slows development. Toward accelerating development, we have made GitHub posts of modifications to the Arduino-SerialCommands library, allowing execution on the Linux command line. While we found anecdotal reports of $\sim 10\times$ compute performance of C vs. Python code on the RP2040, we presently find much more developed SPI-based RC522 ports for Python than C. This software is (from an operating perspective) likely to be more "I/O bound" than "compute bound,' suggesting that at least for prototyping purposes, Python may initially be a more strategic choice after all. The mechatronic, 3D print, and circuit board elements of these designs are provided CC BY-NC 4.0, with LGPL software developments continuing to evolve.

4.5 Hexmaps, hex tablets, and hex drums

With many NFC readers, we have noted a read range at a distance comparable to the read antenna's radius [15, 22]. When we observed this to be so, with low-profile hextok plinths with read-antenna configured in the horizontal plane, this raised the prospect for reading NFC tags both *above* and *below* the NFC reader. This raised prospects for reading individual tags, or fields of tags, located both above and beneath the plinths. With the growth in popularity of hexmaps (e.g., board games like Catan [38], hexagonally-tiled geographical maps [21], etc.), we felt such use holds strong potential.

Staging tags both above and below the plinth raises the prospect (and in some cases, desirability) of multiple tags simultaneously present within the read volume. In RFID/NFC terminology, this is called a "collision." While many NFC reader chips have anti-collision support and multi-tag resolution *hardware* capabilities, firmware and software libraries (especially for low-cost and/or open-source) often do not have include this support. Our particular NFC reader (using the NXP Mifare RC522 chip, available on circuit boards with integrated antenna at ~US$3 cost) had both RS232, I^2C, and SPI support, allowing multiple readers to co-exist on a single embedded controller bus. Figure 8b illustrates one such use, as does our 60-degree reader offset design in Figure 8f-g.

Figure 9a-e illustrates several of our early hexmap iterations. Figure 9a-b depicts a constellation of NFC tag underlays and a side-facing RGB LED strip weave under a regular hexagonal tesselation. The particular LED strip pattern illustrated, with interleaved in-

Figure 9: Hexmap variations

and out-oriented side facing LEDs, allowed tiers of low-density, low-cost, addressable RGB LED strips to efficiently ~back-illuminate the hexmap. Figure 9b shows one 3D print scaffolding of this, with a low-density no-support 3D printed scaffold (printed upside-down) elevating a regular array of NFC tags to just below a printed hexmap; and scaffolding both for guidance of the side-facing LED strip weave, and for the bottom-sensing hex plinths. The two NFC readers visible at the top-left and top-center of the 1'×1' hexmap allow identification of a full or half panel NFC-tagged paper/film overlay(s).

While this seemed technically promising, from an interaction perspective, the use of hexplinths as mobile ~cursor physically obscured the labeled content upon which they were placed. The up-facing bicolor e-paper display prospectively integrated within the Figure 8d hextok plinth variation illustrates one path by which the selected content could be re-mediated. That said, we felt continuing visibility for the printed hexmap might often be preferable.

With a 125 kHz RFID tag technology (more prevalent in past decades), a transparent-core hand-wound RFID reader antenna coil – potentially of hexagonal geometry – would have offered a simple, promising approach. However, to our understanding, 2.4 GHz NFC technologies like NTAG are comparatively more sensitive and less forgiving.[3] As a workaround, Figure 9c places as the NFC reader at a 45 degree angle to the horizontal plane. We found this provided sufficient electromagnetic coupling with the embedded NFC tag to allow reading, while allowing a kind of "functional optical (near-)transparency" to human eyes. (with an edge-on vs. face-on profile) under many viewing configurations. This reduces the profile from 4×6 =24 cm^2 to ~1 cm^2 of effective occlusion. When used in combination with the under-surface LED strip weave, the LED weave could potentially provide visual feedback to indicate the plinth-token's presence and activity. As pictured in Figure 9c, we explored a partial LED strip (visible as a white curved surface around the base's perimeter), and a circular OLED display (the blue circle, shown without simulated content) as complementary displays for mediating computational associations and dynamics.

We also explored terraces of layered hexmaps (Figure 9d-e). Here, we explored illumination of hexagonal cells both from above (especially for lower layers, where an overhead support layers was usually already present) and below. One approach explored were hexagonal extruded baffles around the perimeters of unlensed addressable LED strips, toward directing and shaping the light. Here, we noticed several things. First, for the uppermost layer, we found it challenging to place an overhead LED strip sufficiently close to the hexmap to allow ready illumination, without becoming physically obstructive. Second, in Blender-based virtual versions of the configuration, we found the near-realtime Eevee renderer to lack fidelity with our understanding of the likely optics (caustics); but the Cycles raytracing render required hours per frame on an older CPU (without GPU support) for the shaped illumination to be evident. (This improved to minutes per frame with a high-end present-day CPU and GPU; but still far short of that necessary for on-the-fly rendered 30-240 Hz interactivity.)

Especially in (e.g.) head-mounted display (HMD) cases with virtual tangibles, different virtual illumination approaches would likely be necessary. E.g., Figure 9d illustrates illuminated hexagonal edge-rings. Emissive or additive-transparency polygonal overlays is far more computationally efficient than direct simulation of the physical implementation. This speaks to variations in implementation between modality (esp. between virtual and physical forms), rather than strict adherence to a single form and mechanism. We have begun investigating cases where animated renders using simple Phong shading, with higher fidelity lighting (pre)rendered and cache, often in the cloud, for stable configurations.

Where (e.g.) menus and dialog boxes have historically been essential interactors in graphical interfaces, they are rarely the *only* interactive elements. Similarly, we imagine hextoks might typically be one of many elements within interactive systems. Figure 10 illustrates several variations of this. Figure 10a illustrates three hex plinths and tokens partially surrounding a multitouch tablet. Here, the ~digital shadow of a hextok's face flows into the row(s) or column(s) of a visualization spreadsheet [16, 37, 41] as a form of tangible query interface [52, 76, 85]. E.g., in the right margin,

[3]To our understanding, there are no intrinsic electronic reasons why this is problematic; but that it is likely not resolved by wrapping a certain number of enameled-wire turns around a laser-cut or 3D printed core, as common for 125 kHz readers.

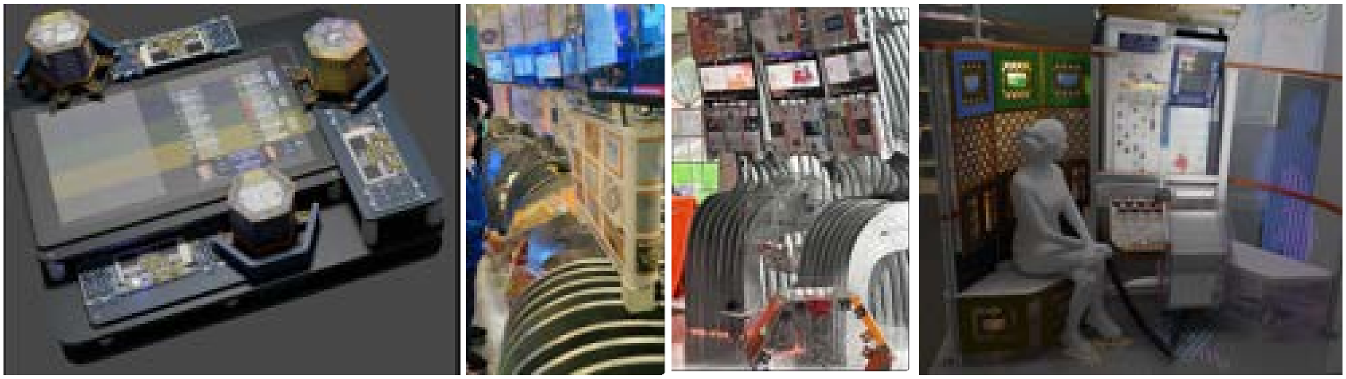

Figure 10: Hexplinth tablet integration; hex drums within larger installations

the hextok expressing six TEI-aligned ACM conferences is placed with the "CHI" face directly adjacent the tablet. Correspondingly, the top (most recent or more highly-cited) CHI papers meeting the horizontal-axis constraint are displayed in the intersecting cells. The adjacent faces of the hextok (here, CSCW and UIST) are displayed in the adjoining rows. Touch interaction with either the screen, the plinths, or the hextoks would yield corresponding updates on both screen and token illumination. Partly per the limited tablet screen real estate, we tentatively located two-color e-paper displays, each with three illuminated clear polycarbonate bolts (ringed with capacitive touch-washers) for selection of relevant hextok parameters (as depicted in the described software state, sorting results by recency vs. citation count).

Figure 10b-d illustrates several additional variations on integration within larger systems. For museum and festival deployments, we sought to provide access to multiple hexmaps and other "interaction panels," while keeping these elements physically tethered to avoid their removal. (E.g., the festival hosting Figure 10b received roughly 10,000 visitors per day.) We were inspired by the Ramellian Bookwheel (Bücherrad) [17, 91], some which were hexagonal in shape. We incorporated the resulting hex drums in several deployed (Figures 10b-c) and virtual (Figure 10d) versions. Figure 10d, intended for lower-traffic library deployment, also integrates hextokens within the console. We have prototyped scale models of these installations (e.g., at 1:12 scale), including for HMD-mediated VR and XR use. There, our original-scale hextokens serve as promising proxies for the larger hexdrums and their interactive contents.

4.6 Blinks-evolved hextoks

Both toward classroom and broader use cases, a path for realizing hextoks with pre-existing electronics and products can be accelerative. Move38's Blinks hexagonal tangibles [11] are presently the closest approximation of which we are aware. At 3.86cm vs 5 cm flat-to-flat, these are substantially smaller than our design. While only a 30% difference in length, this represents a 67% reduction in surface area, at 9.7 cm^2 vs. 16.2 cm^2. Especially for text along the edges, we found this difficult to accomodate. On iteration, we found that using a 3D printed jig holding 7/32" long 0.166" ID 0.25" OD aluminum spacers as light pipes, we could realize a 5 cm flat-to-flat housing, sensed and illuminated by the Blinks modules. This represented a combined 11.1mm increase in optical range. (We found 2" flat-to-flat, at 50.8mm and 12.7mm cumulative extended length, to be out-of-range.) These are pictured in Figure 11. We are presently beginning work with the serial-uplink Development Blink (and possibly, with custom optocoupler board for variations on the above hex plinths) to couple these with external computation. We provide the STL files CC BY-NC 4.0.

Figure 11: Move38 Blinks tokens: 3D printed scaffold with aluminum light pipes

On discussion with the Move38 team, we understand that the Blinks infrared transmitters themselves are of a kind used in remote controls, and capable of transmitting over several meters.[4] The current Blinks behavior is possibly analogous to the way off-surface hands are detectable but filtered by modern multitouch devices, and possibly through hardwired reduction in transmitter power (also desirable given the button cell source). These indicate possibilities for future hardware, firmware, and/or software evolutions that do not require (e.g.) aluminum beamshaping.

The Move38 Github repository also includes developmental "BlinkLink" code for special Blinks blocks providing wireless uplinks.[5] We have begun investigating if (e.g.) Raspberry Pi Pico RP2040 W hardware (including Wifi and Bluetooth Low Energy/BLE support), together with a compact in-facing QTR infrared optocoupler, can provide hexplinth behaviors and connectivity for Blinks and their evolutions (e.g., using Pico edge-triggered hardware interrupts to allow physically reshaped optical relay capabilities, even without disclosure of the currently proprietary protocols).

[4] https://github.com/Move38/Move38-blinks-pcb/
[5] https://github.com/Move38/Blinks-SDK/tree/dev

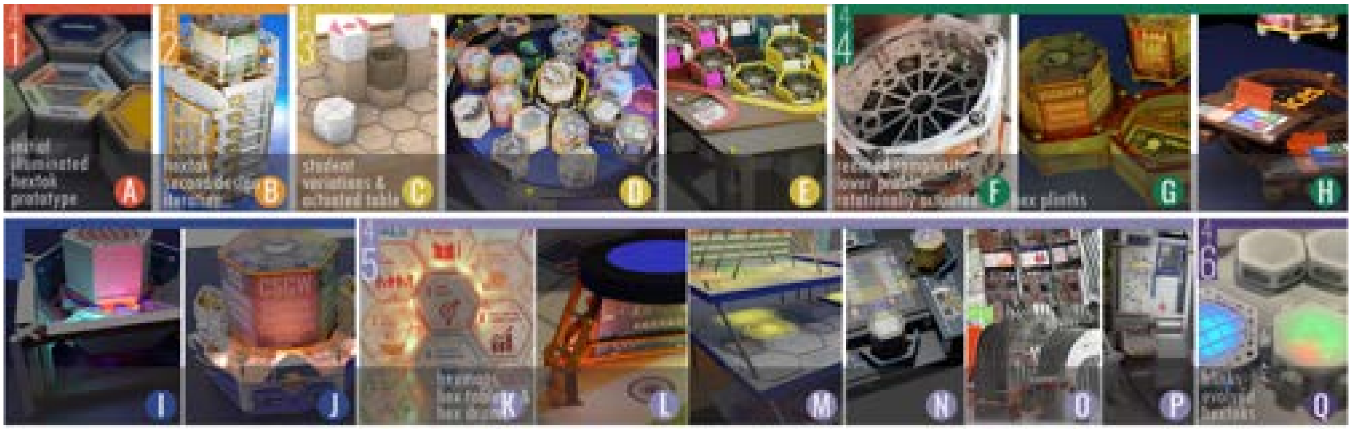

Figure 12: Labeled summary of major hexagonal token + plinth design variations

5 HEXAGONAL TOKEN & CONSTRAINT DESIGN SPACE APPLIED TO NEW PROTOTYPES

In Figure 2, we presented a design space for representational facets of prior polygonal token and constraint systems. We now revisit this space for our investigation of many variations on hexagonal tokens and plinths. Figure 12 provides an illustrative image, the section number (top-left), and a label (A-Q, bottom-right) for each major variation.

Figure 13 positions these prototypes within the earlier design space, again highlighting design choices and variations sharing common properties.

5.1 Tokens and Constraints

First, we sought patterns expressing tangible and intangible (e.g., screen-based) facets using tokens and constraints.

- *screen-embedded hextoks:* Three prototypes (G H L) incorporated e-paper, LCD, or OLED screens within hextoks (or hex plinths, acting at the boundary of token/plinth behavior), which we grouped as illustrative of intangible/screen-based representational strategies.
- *LED-embedded hextoks:* Q A illustrated the use of LEDs directly within hextoks, both with and (thus far) without additional textual or iconic labeling.
- *passively-labeled hextoks:* B C D E F I J N P all illustrated use of passive printed labels (and in some cases, passive 3D printed elements).
- *no tokens:* Three prototypes (O K M), centering on hexmaps and hex drums, did not employ tokens per se.

For tangible and cyberphysical constraints, we have illustrated the following patterns:

- *kinetics and display hexplinths:* E D illustrates kinetics and dynamic displays integrated within hexplinths (with E illustrating a more uniform constellation, and D with varying degrees of mediation;
- *high-resolution hexplinth displays:* G H illustrate high-resolution display integration within hexplinths (a "right-ward" bias toward intangibility), while
- *low-resolution hexplinth illuminations:* B F I J N P illustrate low-resolution illuminated hexplinths.
- *printed illuminated constraints:* K L M demonstrate illuminated, printed hexagonal constraints, but (at least as pictured) without additional mechatronic structure;
- *kinetic hexplinths:* C illustrates kinetic hexplinths, with illumination dynamics provided in associated hextoks;
- *relative constructive constraints:* Q illustrates a case where magnetic guidance provides "relative" constructive constraints, but without an explicit underlying constraint space;
- *hextoks without constraints:* A O illustrate hextoks used without underlying or mechatronic relative constraints.

5.2 Display modalities

- **visual:** all initial prototypes have employed visual dynamics through screens and/or illumination.
  - *tangibles-embedded screens:* G H L integrate small screens within the top of hextoks and/or hexplinths; and E, small screens less prominently for "digital shadowing" on the sides of hexplinths.
  - *tangibles-proximal screens:* N O P integrate medium and larger arrays of screens and/or illuminated surfaces as resources for mediating interactions;
  - *plinth-illuminated hextoks:* B I J D F provide hexplinth-sourced illuminations of hextoks, while
  - *internally-illuminated hextoks:* A C Q illustrate internally-illuminated hextoks.
- **audible:** B H were explicitly conceived with audio as a primary modality of hextok mediation; while none of the other prototypes have engaged audio to date.

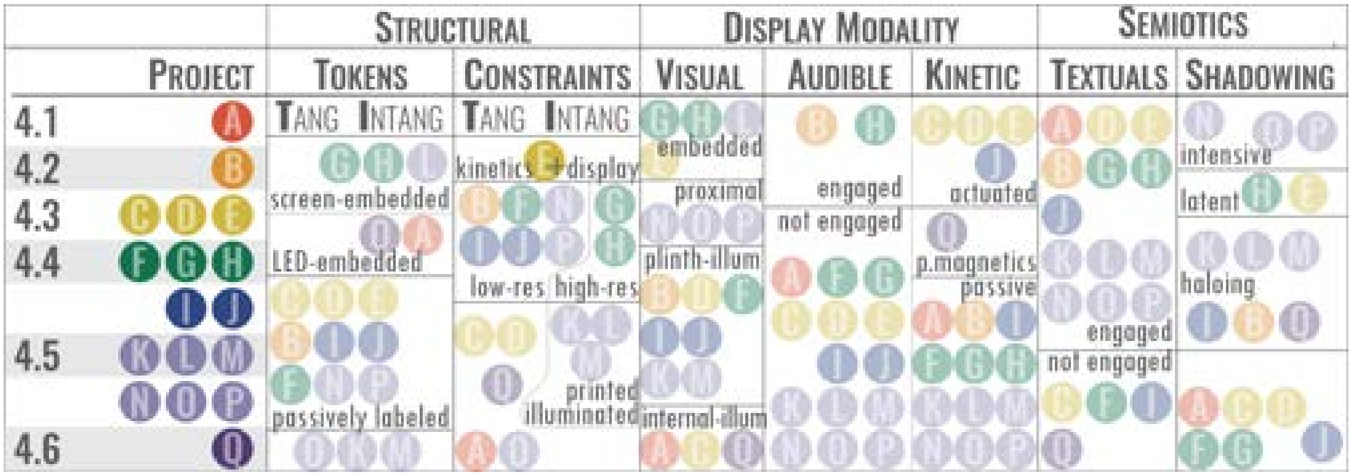

Figure 13: Hextok and hexplinth prototypes, positioned within earlier design space

- **kinetic:** C D E J were explicitly conceived with kinetics as a primary mediation modality. Q, through its magnetics, employs passive kinetics.

5.3 Textuals and shadowing

The careful integration of textual labeling within hextoks has been a high priority. In some respects, this is comparable to the careful labeling of app, file, and behavior icons within desktop and mobile operating systems. Through this, A D E B G H J K L M N O P all illustrate our attentions to text. C F I Q do not yet illustrate this; but for most, this is reflective of developmental stage and visibility of internal mechanisms rather than final design intent.

Digital shadowing has also been a top priority [39, 46], with more mixed evidence in our visuals. N illustrates digital shadowing from the hextoks most clearly. O P also make intensive digital shadowing use, but primarily in the context of illuminated paper elements that are beyond the scope of this paper (and not readily visible in the present images). E H, through mini-screen proximity to hextok sides, prospectively offers strong shadowing potential, though this is not well illustrated in our examples.

With the K L M hexmaps and the B F G I J plinths, our digital shadows intentions evolved more into digital haloing – interactive semantic highlighting of textuals, iconics, and printed physical forms with shaped, colored, context-sensitive light. This terminology has prior engagement [25, 56]. We anticipate much opportunity remains, both conceptually, aesthetically, functionally, and technically, to further characterize and apply this intersection of ideas.

6 DISCUSSION, LIMITATIONS, AND FUTURE WORK

We began this manuscript with Simon's description of complex systems, "made up of a large number of parts that have many interactions ... [i]n such systems the whole is more than the sum of the parts in the weak but important pragmatic sense that, given the properties of the parts and the laws of their interaction, it is not a trivial matter to infer the properties of the whole." [28, 79] Even more so than at our effort's outset, we feel this well-describes the specific projects we have described above – and many facets of the TEI community's larger project.

We have presented 17 iterative prototypes of hextoks and hexplinths. All go far beyond "rough sketches;" most were 3D printed, laser-cut, or CNC-routed; most were made partially functional with embedded processors, NFC tags and readers, etc.; and several were prominently installed (one at the ACCelerate Festival in the Smithsonian National Museum of American History, which received more than 30,000 visitors).

A more traditional approach would be to take one of the 17 prototypes, reduce fully to practice, and evaluate with human subjects. For instance, we developed our second hextok + hexplinth prototype from June 2019 until March 2020 (the full arrival of the COVID-19 pandemic). This effort required roughly 2,000 SVN repository checkpoints by the lead developer, each perhaps representing 15 minutes of design effort. (Since then, development has received more than 10,000 lead developer SVN commits, and many others on github, toward hextoks+plinths and two sister applications.)

With hindsight, redirecting those to a single reduction to practice could have been interesting. But the complexity of the first variation seemed likely to require »10 hours of consumer-grade 3D printer print time and several hundred USD per plinth (at a physical size >> 10*x* larger than our more recent iterations). Our driving use cases involved 10 or more such plinths per installation, with multiple installations, centering around Raspberry Pi processors that have remained nearly off-market for several years. This design also would not support remote-synchronized actuation or multi-rotor hextoks (allowing, e.g., all ~30 of the Slot Machine's control cards [64] to be combined into a single three-rotor hextok); we consider both highly promising.

We view the present diversity of synergistic approaches we have summarized – both in physical and virtual form – as among the greatest potentials for this work. For a student interested in the microservo actuation of the prototype in Figure 8h-j, she need not wait for the tangible operating system we have described; she can make a ~two-hour print of the provided file, connect the US$3 microservo with the US$6 Raspberry Pi Pico W, and begin iterating. If she wishes to explore the dynamics between hundreds or thousands of these, rendering all of them in a head-mounted display with the provided files might be equally attractive; or perhaps reifying one or a few plinths and tokens in physical form, vaguely analogous to a cursor, cyberdeck, and/or potter's wheel. If the tangible operating system itself; the materiality and fabrication provenance of the hextoks (be they of upcycled post-consumer waste, ice, or flowering sod); or variations specific to visually or cognitively impaired users – each might benefit from keeping most aspects of the provided or community-evolved reference design constant, and iterating upon specific aspects of primary interest.

Our manuscript has made sparse mention of underlying software and prospective data models. For representing hextoks' cyberphysical associations, we have prototyped many variations in the human- and machine-readable YAML dialect [8]; many ecologies of relational data in SQLite [61] and SWI-Prolog, with multi-user synchronized content via TUIO [49], with higher-level system representations cached in tools like PostgreSQL and MariaDB with interaction notifications via publish-subscribe hooks. We also continue to pursue interaction software prototypes in PyGame Zero (some with large caches of pre-rendered, alpha-composited visuals, amenable even for weak processors like the Raspberry Pi Zero), with other prototypes employing commercial interaction environments like Unity. Some such data and software prototypes are presently publicly hosted in Github:

https://github.com/ullmer/tangibles/tree/main/manuscripts/tei24

Throughout the manuscript, we have made references to environmental and sustainability dimensions – whether the use of wood vs. steel within hextoks, of PETG 3D printing filament potentially sourced from ground and extruded drink bottles, and the cyberphysical question: should the hextok be virtual, physical, or both. These reflect the increasingly pointed urgency of a climate crisis widely described as perhaps the single greatest threat and challenge to humanity. This is being met by increasing engagement from the HCI community generally [24, 32], and TEI specifically [12, 23, 88]. Here, one observation of relevance is by Gary Hirshberg, speaking of his experience in scaling up organic yogurt manufacture:

> A couple years ago, when we thought there was an organic milk supply shortage, we found a surplus of milk in New Zealand where cows are all grass-fed. We discovered we could, on a carbon-footprint basis, get organic dry milk product from New Zealand to the U.S. with a lower footprint that buying it from the Midwest and bringing it to New Hampshire. [34]

From this, a primary reason we have used "cyberphysical" in our title, rather than our original "tangible" intent, is toward heightening potentials for engaging a progressively more diverse, chaotic world, where assumptions and actualities regarding tangible/virtual tradeoffs vary widely across place, time, preference, and environmental responsibility. We hope the approach we have described could (with iteration) generalize well beyond hextoks and tangibles.

7 CONCLUSION

Many millions of embedded hobbyist-targeted processor boards have been sold (e.g., more than 50 million Raspberry Pi units alone) [78]. However, to our awareness, relatively few individual applications have become focal applications for applied use by broad populations of users. As Jenkins and Bogost write [45]:

> Indeed, one of the distinguishing features of the Arduino landscape is that there is no such thing as mass-produced Arduino project: with the exception of the fabricators producing the prototyping boards themselves, Arduino projects are one-offs, art projects, midterms, and hobbies; at their closest, they represent the output of a fledgling group of hobbyists who produce hardware for other hardware hobbyists. As a platform, the Arduino has dramatically increased the population of people interested in producing, sharing and being excited about electronic hardware manufacturing. At the same time, the dearth of "exit strategies" and successes for the platform may mean that Arduino for most people is both the beginning and the end of a hobby creating electronic objects. [45]

These words have further TEI-specific resonance. Even in the 18^{th} convocation of ACM TEI, to our understanding, these words from our first panel remain true:

> some participants suggested that more complex computation should be occurring behind the tangible interface, instead of only one-to-one input-output. [35]

We have long felt deeply resonance with the "reality-based interaction" aspirations of Jacob et al. [40], toward interaction paradigms that transcend (e.g.) VR, AR, or TEI specificity. Simultaneously, we are less concerned about (e.g.) physical-world metaphors per se, than the realization of specific primitives that equally lend themselves to (e.g.) TEI, VR, handheld multitouch, and desktop variations. We believe the hextok and hexplinth interactors, and the resources that we have provided in support of their physical and virtual realization, hold strong conceptual, perceptual, and pragmatic potential for advancing the state of cyberphysical interaction.

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