Envisioning Tangibles and Display-rich Interfaces for Co-located and Distributed Genomics Collaborations

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ABSTRACT

We explore how pervasive displays could offer unique opportunities for enhancing discovery and learning with "big data". In 2012-2014, our collaboration across three universities undertook a series of design exercises investigating approaches for collaborative, interactive, tangibles, and multitouch-engaged visualizations of genomic and related scientific datasets. These exercises led to several envisionments of tangible interfaces that employ active tokens and interactive surfaces to facilitate co-located and distributed engagement with large datasets. We describe some of the motivation and background for these envisioned interfaces; consider key aspects linking and distinguishing the designs; and relate these to the present and near-future state of the art for tangible and multitouch engagement with pervasive displays toward collaborative science.

CCS CONCEPTS

Human-centered computing → User interface design; Human-centered computing → Interface design prototyping

KEYWORDS

Tangible genomics; collaborative genomic interfaces; tangible interfaces; pervasive collaborative scientific displays.

1. INTRODUCTION

Both the first (2012) and latest (2019) "Pervasive Displays" venues frame pervasive displays in terms of a "new communication medium for public and semi-public spaces." While altogether a less common thread in this forum, the pursuit of science also is centrally concerned with communication in public and semi-public spaces. For example, Francis Crick (co-receiving a Nobel Prize for his contributions to the first characterization of DNA) asserted "communications is the essence of science" [1]. The context of DNA's characterization was not entirely unproblematic; it was partly made regarding Maurice Wilkins' sharing of the transformative "Photo 51" by Rosalind Franklin's doctoral student without Franklin's approval or knowledge [2]. But it does speak to the frequently collaborative nature of modern science. Illustrative examples include the 5,154 authors on a Higgs Boson paper [3]; more than 1,000 authors on the paper reporting the LIGO consortium's Nobel-winning observations of gravitational waves [4]; and (for one of the authors) participation among more than 700 co-authors on two high-impact human genomics papers [5, 6] (with more than 5,000 citations each).

In our experience, these large collaborative projects incorporate several facets and phases of "communication… in public and semi-public spaces." Loosely framed in terms of "when what is communicated with whom," early stages of scientific research can be seen as spanning a spectrum between private and semi-public. Even in the context of large consortium projects, students generally would share results with advisors and within their research group prior to sharing with wider audiences. An academic research lab could well be considered a semi-public space. Similarly, a broader research consortium (common for large science projects) that collaborates toward shared scientific ends also can be regarded as semi-public space.

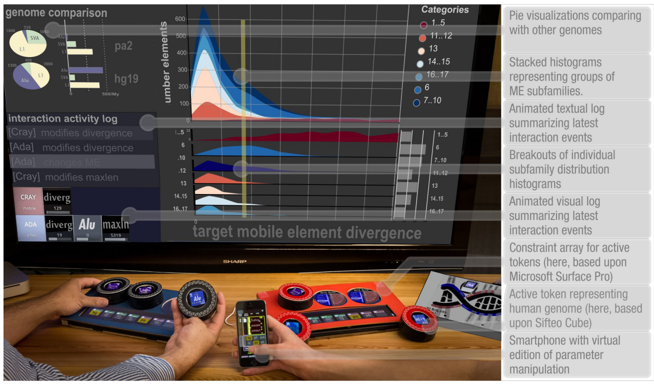

Figure 1: Envisionment of "Tabula" tangible genomics workbench (2014), tablet-based edition. Extracts from our existing genomics code & animated visual log prototypes integrated within a vertical screen, three tablets, six Sifteo-based tokens, and a smartphone. (Sifteo cubes introduced in §4.) These physical tokens & constraints leverage tangibility by supporting collaborative parameter token manipulation while eyes are oriented toward the shared screen or collaborators. Stacks of tokens were anticipated, per [15-18]. Bottom left: the Alu element is logged as impacted in an interaction event upon removal of the token.

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Such work often is constrained by at least two forms of "embargoes," as one "red line" distinguishing "public" from "semi-public." In genomics contexts, the Bermuda [7], Ft. Lauderdale [8], and Toronto [9] agreements all govern conventions by which data, which is commonly made publicly available as it is generated, can be commonly engaged but not published in the interim (sometimes many years) without consent by the consortium before the first major "marker" publication is realized [10, 11]. Press embargoes are also factors, but typically for much shorter periods [12].

Especially prior to pre-publication data embargoes, it is common for hundreds of researchers spanning dozens of institutions to vigorously collaborate for years. Tools to facilitate scientific dialogue, going beyond emailed slides before voice conference calls, hold potential for high scientific impact. Collaborating institutions commonly bring different disciplinary expertise, sometimes from different disciplines, increasing communication obstacles already posed by distance. This heterogeneity is often replicated in smaller form within individual research groups, both across seniority and disciplinary focus (e.g., computational methods vs. basic natural science).

Once work is published, a new ecosystem of "semi-public and public spaces" can be seen to exist. Some of these are in the context of formal education, be it postgraduate, undergraduate, or K-12. Others engage "broader impacts" outreach efforts, be they through museums, non-classroom K-12 activities, or others. Both for larger and more moderate government-funded scientific efforts (e.g., as with LIGO), these are often either encouraged or mandated as a condition of funding, toward eliciting greater engagement with students and the general public. Our genomics interests in particular hold criticality beyond basic "scientific literacy," to a more fundamental literacy that will reshape our medical care, and may even impact people's ability to hold employment or make prenatal or even preconception decisions [13, 14]. Thus, this is of profound relevance to all humans. Here, too, "new communication medium[s] for public and semi-public spaces" hold special potential for impact.

To connect these discussions to the pervasive display domain, one of our envisioned, partially prototyped interfaces is illustrated in Fig. 1. From the pervasive display vantage, we note the relative ***density*** and (in some respects) ***heterogeneity*** of interactive displays depicted within. Fig. 1 represents (at least) one large, three medium, and eight small interactive displays manipulated by several individuals within a relatively small (several square meter) area. Similar technological resources might potentially span a much larger extent both in one physical site; and potentially bridge synchronous or asynchronous interactivity with interfaces at other physical sites (whether pairwise, tens, or even many thousands).

2. BACKGROUND AND RELATED WORK

One major challenge in computational genomics relates to the scale of datasets. Many genomic research efforts involve the study of multiple genomes. Today this may involve a thousand or more genomes in parallel, each containing billions of DNA base pairs. Soon, such scenarios may involve millions of genomes. There is a need for new computational tools for analysis and that facilitate meaningful interactive engagement with these vast datasets. Present interaction tools for computational genomics rarely venture beyond traditional graphical interaction techniques, thus missing the latent potential of alternate interaction paradigms.

Tangible and embodied interfaces (TEI) offer unique opportunities for enhancing the practice of computational genomics [13]. However, TEI research has not yet addressed scale and complexity of this magnitude. Understanding how to support more complex computations and flexible/scalable mappings between input and output has been recognized as an important challenge area to move the field forward [19].

Many arguments supporting tangible interfaces have been made, including cognitive, pedagogic, aesthetic, kinesthetic, and cultural [20-23]. In parallel, important limitations for tangible interfaces remain. Challenges include the development of interfaces that go beyond one-to-one mapping, and provide means for searching, comparing, and sharing big data. Which representations are appropriate for large volumes of abstract data? What interaction techniques could facilitate fruitful exploration of big data? How can we effectively combine representations and manipulations to potentially reduce the mental workload associated with handling big data? Furthermore, as communication is frequently key to the success of genomic investigations, how can we best manage work across multiple co-located users, given the complex workflow and broad temporal range of interactions (from seconds to years)?

Direct touch has become a standard input method for tangible and multitouch interfaces. Yet, in data-intensive applications, representations are typically small [24]; here, finger size and occlusion make direct interaction difficult [24-26]. Also, in data-intensive applications, WIMP-style control elements provided by various multitouch toolkits, such as scrollbars, sliders, checkboxes, and text fields, may often be either too small for effective and accurate touch interaction, or consume relatively limited screen real estate [24, 27]. Several studies have considered novel multitouch interaction techniques for data-driven applications [24, 26-28]. While providing advantage over touch interaction with WIMP-style controls, multitouch gestures often suffer from low discoverability and lack of persistence [24]. We considered an alternative approach: exploring large data sets on multitouch and tangible surfaces using tangible interaction with active tokens, complemented by multitouch and gestural interaction.

Active tokens are programmable physical objects with integrated display, sensing, or actuation technologies [15, 29, 30]. Thus, they can be reconfigured over time, allowing users to dynamically modify their associations with datasets or controls. Users can thereby choose and evolve appropriate tools over successive stages of (e.g.) scientific workflows. Active tokens can also be arranged in various spatial configurations, utilizing physical syntax to represent complex information workflows. The majority of tangible interfaces to date have, from a human sensory perspective, employed passive physical tokens. While these artifacts have often been embedded with various forms of tags and sensors, mediation has typically been via active surfaces illuminated internally, from beneath, or above. While they can support perceptual coupling of bits and atoms [31] or "coincidence of input and output space" [32] while on such surfaces, passive tokens are often perceptually divorced from their digital associations when in hand (above a surface) and in reserve (on or outside of surface bezels). Especially in big data domains, the number of available tangibles is likely to be dwarfed by their potential range of digital bindings (or "cyberphysical associations"). Active tokens hold the potential to address these and other important limitations.

Here, we focus on a subclass of active tokens that can be manipulated both within mechanical constraints, and using gestures independently from such constraints. These kinds of active tokens enable the expansion of tangible interaction with multitouch and tangible surfaces beyond interaction on the surface into less explored areas such as tangible interaction on bezel, in air, hovering above, or in front the surface. Expanding interaction with active tokens beyond the surface could free much needed real estate for visual data representations, among other potential benefits.

3. COMPUTATIONAL GENOMICS & BIG DATA

While TEIs designed for large data sets can apply to many different areas, we have chosen computational genomics as a target domain for our research for several reasons. Advances in genomic technologies have transformed biological inquiry, and have begun to revolutionize medical practice to offer much-improved healthcare [33, 34]. For example, cancer treatment is now often individually tailored toward the genetics of the cancer, highlighting the potential of precision medicine and providing a glimpse into the future of medical treatment. Also, genomic and biological technologies are positioned to address some of the most pressing problems of our times, including food and clean water shortages, as well as in- creased demand for alternative energy sources [39]. Further, the field of genomic technologies has opened new interfaces between biology and computer science, fueling fields such as bioinformatics that enable biological questions to be tackled computationally [33].

Resonant with broader evolutions in science [35, 36], the study of genomes now engages theory, experimentation, and computation on equal footing. The combination of advanced genomic technologies (e.g. high-throughput DNA sequencing) and powerful computational tools has facilitated biological investigations in previously impossible manners and scales [37]. No longer limited to small-scale analyses (e.g., of a few genes or specific genomic regions), researchers now often conduct large-scale experiments where information from multiple genomes is measured, recorded, analyzed, and stored. The bottlenecks and challenges along the path to transforming the "big data" generated by these experiments into biological insights have shifted from data generation to data analysis [13, 33]. These have highlighted the need for new computational tools that facilitate effective, meaningful, collaborative analyses.

3.1 TEI systems for scientific understanding

A number of systems illustrate possibilities for supporting scientific discovery and higher education with TEI. Brooks et al. [38] developed the first haptic display for scientific visualization. Gillet et al. [39] presented a tangible user interface for molecular biology that used augmented reality technology to view 3D molecular models. Schkolne et al. [40] developed an immersive tangible interface for the design of DNA molecules. Grote et al. developed a tangible user interface for bio-design that supports a scientific workflow that requires the exploration of large datasets through the construction of complex queries [16]. While these systems highlight potential benefits of TEI for scientists, they mostly focus on the representation of objects with inherent physical structure. We are interested in a broader use case, where abstract information (for which no intrinsic spatial representation typically exists) is represented and manipulated.

Several projects investigate augmented capture and situated access to biological data. Labscape [41] is a smart environment for cell biology labs. ButterflyNet [42] is a mobile capture and access system for field biologists. Mackay et al. and Tabard et al. [43, 44] explore the integration of biologists' notebooks with physical + digital information sources. While these systems demonstrate the feasibility of augmenting experimental workflows, our focus in these efforts has been upon transforming data into insights.

Other systems have been developed to facilitate collaboration among co-located teams of scientists across large displays and multitouch tables. WeSpace [45] integrates a large data wall with a multitouch table and personal laptops. TeamTag [46] allows biodiversity researchers to collaboratively search, label, and browse digital photos. Isenberg et al. studied collaborative visual analytics [47]. eLabBench [44] investigated tabletop interfaces as interactive wet lab benches. Kuznetsov et al. explored the development of artifacts for supporting DIYbio [48]. Other related resources include coordination policies and guidelines for co-located groupware [49, 50] and evaluation methodologies for collaborative environments [51-53].

TEI systems have also demonstrated potential to support science education. Those most relevant to genomics include Augmented Chemistry [54], a tangible user interface for chemistry education; Involv [55], a tabletop interface for exploring the Encyclopedia of Life that shares our challenge of creating effective interaction techniques for large data spaces; and PhyloGenie [56], a tabletop interface for collaborative learning of phylogeny through guided activity. In contrast to these works, we are interested in the development of interfaces that empower both expert and novice researchers to conduct open-ended hands-on inquiry.

Figure 2: "Tabula" tangible genomics workbench (2012).

4. TANGIBLE GENOMICS ENVISIONMENTS

With this background, we turn to several envisionments of prospective tangible genomics interaction environments.

Both of our envisionments have been framed in the context of a several square meter workspace. Each could easily (and perhaps preferably) be room-spanning. As each was anticipated to be installed within at least three different university contexts, we tended toward self-contained prototypes. Both systems reflect our interests in integrating mass-market commodity devices, including several technologies specific to the period. For example, our research programs had each engaged Sifteo Cubes [57-61]. These "cubes" (in actuality, 1.5"×1.5"×¾") contain touch screens and are motion- and proximity-aware. While designed as gaming devices, Sifteo went open source and allows the development of non-game content. Sifteo Cubes use gestures – including tilt, shake, neighbor, press, wiggle, slide, flip, and stack – as modes of interactions.

While a compelling platform for continuing work – in our case, also incorporating special capabilities coordinated with the manufacturer – the Sifteo technology was acquired and discontinued. By the time of Figure 1's creation, we expressed our intent to consider (e.g.) smart watches and small form factor smartphones as alternatives. Similarly, Figure 2 centers around the form factor and functional properties of the Microsoft PixelSense/Samsung SUR40 device. SUR40, too, was short-lived; Figure 1 excised its inclusion.

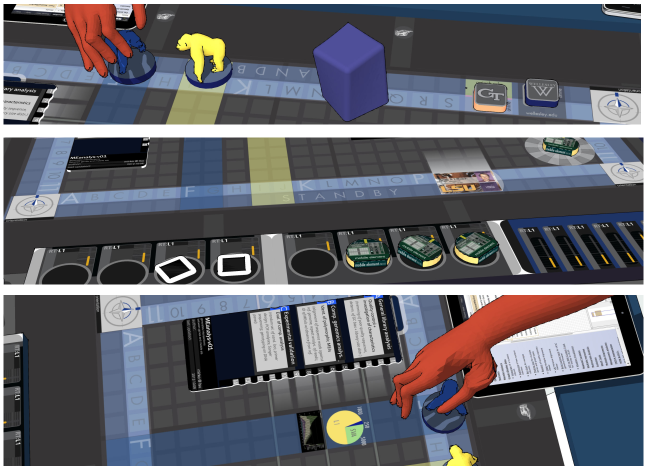

Figure 3a) 2012 envisionment inset 1: genome, genome panel, place/team tangibles; b) inset 2: active and passive parameter tokens: ID as container; parameter pie menus; c) inset 3: workflow tangibles; tablet with linked Galaxy workflow; visualizations

The name of our envisioned system, Tabula, was used for roughly 1,000 years as a term for medieval European "counting tables" – a calculating approach somewhat reminiscent of the abacus, and a predecessor to computational spreadsheets. The information visualization spreadsheet concept [62] also seemed congruent to both multitouch and tangibles use.

We sought to provide paths for employing tangibles to represent the "key objects of interest" [22, 63]. Several specific planned variations included:

- Some tangibles are used to represent data; others, tools;
- Some proposed tangibles are passive; others, active (e.g., incorporating sensing and displays);
- Some tangibles are physically representational (e.g., Fig. 3a; representing different kinds of primates); others, visually representational (Fig. 3b, representing different campuses); others, physically and visually abstract.
- Some interactive elements are physical, others virtual. E.g., Fig. 3b illustrates both "hard" (physical) and "soft" (virtual) tokens representing different campuses.

Rather than expecting all aspects of the interface to be physically embodied, we instead envisioned many system facets at different stages flowing between representation in physical and virtual forms. Thus, we sought to take advantage of digital malleability and proactivity evident in (e.g.) predictive web search, while also engaging the benefits of tangible interaction.

4.1 Prospective Elements

Both in research and teaching labs and in the classroom, we envisioned Tabula engaging ~6-12 active tokens, and one or several interactive surfaces. Each active token could take on various functional bindings. Several prospects are summarized in Table 1.

Active tokens were envisioned to combine with constraint cartouches [64] in several ways. First, they could be bound to different associations manually. E.g., using a two-handed interaction, a user might touch a binding on a tablet or tabletop with one hand, and depress a target token with the other hand. Second, active tokens could be manipulated within constraints to operate upon token bindings. In Table 1's examples, rotating token #1 could select between several available primate genomes (marmoset, gibbon, etc.); rotating #6, expressing a mobile element's full-length threshold (a process which typically requires iterative manipulation to parametrically select anywhere from a handful to hundreds of thousands of target elements). In addition to passive haptic feedback from turning the token, we envision providing active visual feedback on the token itself, on the backing interactive surface, and on a proximal vertical display. These are intended to support evolving views by multiple collaborating users.

Table 1: Examples bindings for Tabula active tokens. Background colors indicate two classes – data and tools; shading indicates subclasses. Some tokens might be bound to a single association; others, to small or large aggregates.

tok #	class	binding	examp. contents
1	data	genome	n primates
2	data	mobile element (ME) type	n ME classes
3	data	mobile element type	n *kothi* variants
4	data	candidate element instance	47 elements
5	tools	analytics tools	RepeatMasker, etc.
6	tools	param	length threshold

4.2 Sample Interactions

Figures 1 and 6 illustrate a prospective interaction comparing Platy-1 mobile elements (a recently discovered mobile element specific to New World monkeys [65, 66]) within the marmoset genome. Rotating physical tokens, or engaging finger-constraining interactions in the empty token wells, were envisioned as allowing the addition or changing of genomes, targeting of mobile elements, and assignment of full-length thresholds. Additional visualizations, primer design, computational analyses, and other actions would be physically or graphically invoked and parametrically controlled through similar interactions. Active tokens could be lifted from the workspace and held, placed, or exchanged with other users to support varying styles of epistemic cognition [67]. Tokens might be virtually or physically brought to (e.g.) a laptop for manipulation in a conventional spreadsheet, or to a wall-scale display for presentation use.

Figure 6: 2014 envisionment inset: Envisionment of Tabula prototype (one edition; inset of Figure 1). Several active tokens are present within mechanically constraining wells within physical cartouche constraints fixtured upon tablets. Two wells are physically empty, but graphically auto-filled with predictive data and tool suggestions, including a default selection. Two of the tablets (relabeled versions of working prototypes) incorporate relatively generic token constraints. A third (envisioned on right) explores more representational finger constraints for relatively persistent data, function bindings.

5. DISCUSSION AND FUTURE WORK

In some respects, the 2014 variation of Figure 1 expresses a subset of the representational forms and proposed functions of Figure 2's 2012 version. Where the 2012 version was targeted toward distributed collaboration, the 2014 version was focused on co-located interaction. Where the 2012 version incorporated both physically representational and abstracted tangibles, the 2014 version was populated primarily with abstracted tangibles. And where the 2012 version anticipated ambitious use of the tabletop display, this was removed from the 2014 version.

That said, to our knowledge, both the 2012 and 2014 interface envisionments illustrated and aspired to a more ambitious set of digital functionality (at minimum, within the context of computational science) and diversity of integrated displays than any to-date tangibles interface of which we are aware. One interpretation is a platform/content tension alluded by Ansoff [68], articulated by Merrill, and elaborated within [23]. Implementing the hardware alone of Figures 1 or 2 is an ambitious proposition, as would be the software alone. Especially with the resources of academic contexts, a direct ad-hoc ***de novo*** creation of the full hardware and software ecosystem is likely to be challenging and fraught. Our team realized this, and sought to position existing software environments like Galaxy [69-71] – an open source environments for genomic analyses targeted toward non-programmers – and platforms like Sifteo and PixelSense [60, 72]. But we also noted a relatively wide functional and API gap between Galaxy and our needs. Also, the Sifteo and PixelSense platforms were already in rapid decline, and the Sifteo remains currently without a commercially available successor.

At the time, our team identified tangible reinterpretations of smart watches as one promising vector. Some of us have pursued this further [73], with some success. Some of us have also partially developed active tokens utilizing ePaper and NeoPixel rings, which could also offer a complementary platform. In all cases, the rapid turnover of hardware platforms (as with smart watches), and the resource demands of platform development, remain significant obstacles. The creation of interoperable virtual editions – both on 2D screens, and also in VR environments – remains one attractive path, if partly as a bootstrapping vector. At the same time, we anticipate a careful balancing act must be made. If, as in our passage from the 2012 to 2014 prototypes (or in another example, the evolution of the Urp tangible interface from initial to classroom-deployed form [74, 75]), there is too much functional and representational dilution, the result may be insufficiently compelling to attract and sustain use and development.

In the present and near-future, we see several promising prospects toward catalyzing the creation of such functionalities. New mediation technologies such as LightCrafter (used for positional sensing by Zooids [76]), in combination with active tokens, could provide paths for tabletop mediation and sensing with newly compelling capabilities and economics. The combination of small, inexpensive ePaper modules and embedded computers (e.g., Wi-Fi integrated Arduinos), combined with 3D printing, could change some of the platform dynamics underlying active tokens. The rapid growth and investments of VR, combined with compelling complementarities between VR and tangible interfaces [77], could drive the creation of software platforms that could accelerate creating such environments.

Continuing evolutions in the smartwatch space – e.g., decrease in the cost of high-function legacy devices, perhaps as inbuilt batteries of Apple watches fail, or as Android variants gain functionality and traction – could reshape the active token landscape. Decreasing costs and new technologies in the sensate large-screen landscape is another driver. The accelerating trajectories of both personal genomics and genomics within academic research – and corresponding demands for and software platforms enabling new interactive modes for engaging genomics – would also be a powerful complementary driver. In a final variation, where low-level protocols like TUIO [78-80] achieved substantial impact and uptake, higher-level sister APIs – perhaps initially in the context of games, music, and other mass drivers – could substantially ease system development for ambitious tangible pervasive displays.

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