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1 Creativity

What is creativity? Creativity – the potential for making something new – is framed by the old, is contingent upon history. As what was once new becomes old and as new challenges, new skills, new technologies, and new possibilities emerge the potential for making something new evolves. Creativity is situated in time, in cultural and social context. It is perceived at temporal scales from the instantaneous to the evolutionary, at scales ranging from the personal – the interior – to the global. Creativity depends upon the perception or experience of newness, a concept that is transient, dependent upon the past, culturally defined, and yet personally determined. Thus creativity is unstable, continually shifting, continually evolving, its possibility, its value, and its definition in constant flux yet constrained by history and context. Creativity allows us to adapt cognitively and culturally as our world changes.

Art – as creative expression – is the evocation of cognitive change (Donald, 2006). Art as an inherently creative endeavor highlights the inchoate nature of creativity. 'The concept of art is located in a historically changing constellation of elements; it refuses definition' (Adorno, 1997). Art's definitions and values shift over time and across cultures – 'much that was not art – cultic works, for instance – has over the course of history metamorphosed into art; and much that was once art is that no longer' (Adorno, 1997). Because art is creative, because art must continuously reinvent itself and evolve in novel, unexpected directions as culture changes, 'art can be understood only by its laws of movement.... It is defined by its relation to what it is not.' (Adorno, 1997).

Charismatic creativity Then again creativity does not seem so mysterious. Psychologists have classified types of creativity, modeled the creative process, and developed metrics for measuring creativity. Creativity has been classified in terms of implementation, novelty, value, and intentionality. Creativity can be personal, novel and significant for the individual, or it can be valued for novelty in a wider context, potentially at a global and historical scale (Drago and Finney, 2014). Wallas modeled the creative process as a sequence of stages – a process of preparation, incubation, illumination, and verification (1926). In this widely accepted model of creativity one first prepares – one begins to think about a problem or endeavor, researching it and developing the skills needed to address it. Eventually one lets their ideas incubate in their subconscious, letting their imagination make novel connections. When a creative idea emerges from the subconscious there is a moment of illumination. Finally the creative idea should be expressed, tested, and verified. Does it solve the problem? Is it valuable? Is it truly novel? (Wallas, 1926; Drago and Finney, 2014).

Such models of charismatic creativity are based on a modern conception of self and Romantic ideologies of natural genius, originality, and individualism. In Romanticism originality is unlearned and inspired from within. Since originality is unlearned, the individual – not their society – is paramount; this spirit of individualism fueled a culture of innovation focused on genius. Romantic ideas of self expression stressed contingency, spontaneity, and unpredictability in creative work (Wilf, 2013a,b).

Wilf argues that with the rise of a 'creative class' in contemporary society there has been a move to professionalize charismatic creativity by streamlining the muse. That the Romantic vision of creativity as an unpredictable, unteachable process that springs from within has become ingrained in

global culture today, but is now being transformed. That our culture seeks to harness contingency and spontaneity as cultural resources in order to make creativity more efficient (2013b).

Flow There are other important psychological and cognitive models of creativity. Csikszentmihalyi proposed that 'flow,' a state of 'intense experiential involvement in moment-to-moment activity' in which action and awareness merge (2014b) was the primary motivating force, the driver of creativity (Csikszentmihalyi, 2014a). While still based on the romantic vision of charismatic creativity flow highlights the importance of action, experience, and emotion. By grounding creativity in the body flow suggests the potential role of embodied cognition in creativity. And if embodied cognition plays a role in creativity then surely situated and distributed cognition must as well?

Conceptual blending Conceptual blending – another model for creativity – describes the subconscious cognitive process by which meaning evolves. This model explores creativity at a fine temporal scale – the instantaneous – and how it unfolds iteratively. In a rapid, subconscious process, two ideas are blended together against a background of shared knowledge so that a novel idea emerges. The two ideas may be mismatched and even contradictory so long as they share something in common. The relationship drawn between these two potentially incongruous ideas creates new meaning. Types of meaning such as a "categorizations, analogies, counterfactuals, metaphors, rituals, logical framing, and grammatical constructions" are formed by blending (Fauconnier, 2000). The process can unfold rapidly, sequentially, and in parallel as blends are blended. In blends of blends concepts can become more complex and nested. Greater novelty and richer meaning can arise as more blends are blended. This is a very different conception of creativity. It is a rapid process. It is situated and potentially distributed and embodied. In conceptual blending cognition is situated in a background of shared knowledge and experience. It may be embodied, drawn from kinaesthetic and emotion experience and expressed in action. It is distributed across existing ideas, shared meanings. It may be distributed between multiple actors sharing creative agency, relying on tools and technology.

Embodied creativity Art and thus creativity evolved with cognition. As early humans' prefontal and premotor cortex grew in size and connectivity their metacognitive abilities expanded so that they could reflect on, develop, and eventually share their actions. Roughly 2 million years ago the first mode of artistic expression, the mimetic arts – 'gesturing, pantomime, dance, visual analogy, and ritual' – emerged marking a significant advance in cognition, culture, and creativity (Donald, 2006). Mimesis enabled people to share ideas, technologies, and practices through imitation, rehearsal, and play and set the stage for the emergence of language (Donald, 2006). Mimesis enabled people to embody cognitive processes through action – abstracting ideas through play (Deacon, 2006) and physically simulation (Kirsh, 2013) in order to learn them and adapt them. Adaptation is always creative because every body is unique, mimesis is exploratory, and abstraction introduces novelty. With mimesis humans had the creative ability to abstractly explore and develop ideas with the body. Later when linguistic and then theoretical expression evolved, new modes of creativity and art emerged (Donald, 2006).

In embodied cognition thinking is embedded in the body. Meaning is grounded in emotion, perception, and experience. Higher thought is built upon perception, sensation, and action. Thinking

can happen through action (Hardy-Vallée and Payette, 2008). Creativity, when embodied, should be conceived differently. Embodied cognition relies upon sensory and motor schemas, on parallel subconscious processing. Complex thought processes can be offloaded and physically simulated with the body, processed subconsciously. Because so much cognitive work can be performed subconsciously through action, subconscious creative processes need not be separated into Wallas's incubation stage – the creative process may unfold in rapid, generative iterations in which conscious thought is built upon subconscious thinking-in-action.

Creativity in action While psychological research has been focused on charismatic creativity there are other cultures with very different, more embodied conceptions of creativity. In the Zen Arts, for example, 'creativity is represented as a state of 'nothingness' (mûshin) that is beyond matter and form ' (Cox, 2011), a state of purely embodied, subconscious thinking-in-action. When creativity is embodied there may be no time for incubation, no discrete moment of inspiration or illumination, no linear step-by-step process. While creative performances may (or may not) be choreographed and practiced, the performers make creative decisions while in action. Dancers may interpret their emotions through dance, actors interpret their roles while acting them, and martial artists creatively act and react. Open work – art in which the author, the performer, and potentially even the audience collaborate and develop meaning together – is a radical example of creative agency in performance. In Stockhausen's Klavierstück XI, for example, the performers decide how to navigate through a sequence of fragments, charting their own course across the sheet of music in a highly creative performance that unfolds in action (Eco, 1989).

Deconstructing creativity The role of the individual creative – the author, the artist, the genius – as the sole creative agent, as the fount of meaning has been deconstructed by Barthes (1977) and Foucault (1998). Every creative work is situated in an intertextual network; it was inspired by other works, references others, communicates through them. A work's meaning is not transmitted directly from the creative to their audience; it is filtered by the audience's awareness of other texts, other works, other experiences that informed it. Creative agency unravels, distributed. The reader interprets the work, creating their own meaning. The network of texts mediates, contributes possible meanings, other readings.

Creativity in design The creative process in design disciplines is often described as an iterative process in contrast to the linear model espoused by Wallas. Schön proposed that professionals like designers develop creative ideas through 'reflection-in-action,' an iterative, exploratory process of framing the problem, ideation or making, and critical reflection (1983). This exploratory process may unfold in an instant in action, repeated continually through acts like drawing or model making. Frank Gehry for example develops his designs through exploratory form finding with massing models and by thinking through the movement of gestural drawing (Gehry, 2004; Pollack, 2006).

The iterative nature of 'reflection-in-action' may suggest incremental creative advances, but novelty and efficacy may emerge suddenly as the sophistication and complexity of the idea develops. The choice of (or process of choosing) the frame – a generative metaphor perhaps – is an important creative decision. The frame, however, is not static – it is developed, refined, adapted, and perhaps even discarded and replaced through the creative process. Since conceptual blending describes

how frames such as metaphors and analogies are developed, adapted, and built upon, it may be the cognitive process underlying 'reflection-in-action.'

Yaneva's ethnography of the Office of Metropolitan Architecture showed that architects in the firm used practices like reuse, adaption, and exploratory modeling to develop designs through iterative processes lacking Wallas's sudden moment of illumination (2009). The architects, for example, explored form by carving foam massing models with hot-wire cutters, reflecting on each model as they carved, while building up a library of forms. Ideas and forms set aside and unused in one project might show up in other projects, recycled and adapted (Yaneva, 2009). In design there is a tension between charismatic creativity and collaborative studio work. While the charismatic 'starchitect' Rem Koolhaas dominates the public's perception of the Office of Metropolitan Architecture, Yaneva's ethnography revealed a collaborative studio environment with distributed creative agency (2009).

Assessing creativity Just as there are many models of creativity there are many different methods for assessing creativity. There are methods for assessing an individual's creativity such as psychometric tests (Drago and Finney, 2014), self assessments, peer assessment, and creative output (Csikszentmihalyi, 2014a). There are qualitative methods for assessing the results of the creative process such as expert judgment and evaluation. And there are quantitative experiments for assessing the cognitive response of subjects to a creative product (for example,w a painting or sculpture) using technologies like eye tracking, electroencephalograms, and functional magnetic resonance imaging (Chatterjee, 2014). There are qualitative methods for assessing the performance of creativity like the experience sampling method – randomized self reporting – used to assess flow (Csikszentmihalyi, 2014b). Since there are many modes of creativity, I argue that ethnographic methods such first be used to frame the creative practice in its cultural context. The way in which creativity is conceived in a given context must be established before it can be assessed. Once we have described and framed creative practice in context we may be able to experimentally study the creative process and its results.

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1 Tangible engagement

1.1 Introduction

Theoretically tangible interfaces for geographic information systems (GIS) have the potential to radically transform the role of stakeholders in environmental issues. GIS have the geospatial analyses, models, and simulations needed to scientifically study and predict a wide array of interacting environmental processes. Given the complexity of parameterizing spatial algorithms and working with multi-dimensional data, GIS, however, can be challenging to learn and use (Ratti et al., 2004). If GIS felt so natural to use that stakeholders without any computing experience could use a GIS to explore environmental processes then stakeholders could drive environmental decision-making, radically opening science, design, and management (if political will allowed).

These theses have yet to be demonstrated and proven. The effectiveness of tangible interfaces like shape displays need to be empirically tested (Rasmussen et al., 2012). The ways in which tangible geospatial modeling mediates learning and thinking about processes should to be studied. The effectiveness of engaging stakeholder should to be demonstrated in diverse contexts. A real-world demonstration of stakeholders using tangible geospatial modeling to solve a set of complex environmental problems, alone, would not be enough to understand how and why the process works – if it does – and how it could be improved. Experimental studies in the lab, user studies in the field, and real-world implementation should be coupled with the continued design and development of the technology.

1.2 The importance of engagement

Both pragmatically and ethically it is important to engage those involved in environmental issues like biodiversity conservation. Without engaging those involved efforts to solve complex environmental problems like the loss of biodiversity may be ineffectual and will certainly be unjust. Top-down planning and command-and-control governance has led to the establishment of ineffective conservation reserves in developing nations – to 'paper parks' such as Sierra Chinajá in Quatemala which is threatened by land invasion and resource extraction (Bonham et al., 2008). Citing the inequitable distribution of land and the insecurity of land tenures as the underlying drivers of biodiversity loss in Sierra Chinajá Bonham et al. argue that engaging local people rather than excluding them could transform "squatters' to 'stewards" (2008). To foster local stewardship Brosius and Russell advocate indigenous management in conservation reserves and the devolution of power to local stakeholders (2003). Brosius and Russell also question the validity, legitimacy, and justice of maps made by ' governments, industry, and local elites' which fail to incorporate local knowledge, values, and interests (2003). How can local knowledge be included in maps, models, and simulations?

1.3 Open science

Open science strives for accessibility, transparency, and reproducibility through open access, open data (Boulton, 2012), free and open source software (Ince et al., 2012; Rocchini and Neteler, 2012), and open education (Petras et al., 2015). When science is accessible, transparent, and reproducible it is more inclusive, more critical, and thus more legitimate. The scientific community needs access to research and data in order to reproduce it – in order to test and validate it. The research process should be more transparent so that algorithms, experiments, and data can be scrutinized, reproduced, tested, and critiqued. Theoretically this could fuel the pace of scientific research, lower the cost of research, and build scientific credibility. Open science projects like the Nutrient Network, a grassroots ecological monitoring network, have already delivered rapid and cost effective results (Stokstad, 2011).

Open science calls for a culture of openness, collaboration, and inclusion that could potentially engage a much broader community by, for example, encouraging citizen science. In a truly open science models would be so open that stakeholders could co-develop them and make them their own. By collaboratively developing scientific models with local stakeholders, scientists can 're-distribute expertise' and collectively generate new knowledge (Whatmore and Landström, 2011; Landström et al., 2011). With a series of case studies Sandker et al. show that participatory modeling can encourage strategic thinking across disciplines, highlight underlying drivers of change, and identify trade-offs, but also caution against overly complex models , arguing for 'a balance between 'models as stories' and technical modeling' (2010).

Local stakeholders can also be engaged in and empowered by the collection of open data. In Participatory 3D Modeling stakeholders such as indigenous communities map geographic features, resources, practices, and rights on a physical 3D contour model using familiar, everyday materials such as pins, yarn, and paint to share their traditional spatial knowledge. The 3D model helps situate stakeholders in space in an intuitive way. The familiar media are natural to use as they draw on existing skills. The tangible quality of the physical model and material traces of their mapping promote a sense of agency and ownership. The completed model is digitized, stored, and mapped in a GIS. The physical 3D model and prints of digital maps are left with the community as a resource for education, communication, resource management, establishing land rights, and conflict resolution (Rambaldi and Callosa-Tarr, 2001). The Forage Tracking project, another example of participatory mapping, helped a cooperative of catadores – informal recyclers – in São Paulo to track and map their routes. With the help of the researchers the cooperative mapped their routes using GPS tracking and real-time web mapping. They also collaboratively designed a software platform for community recycling through a participatory process that highlighted the need for trust in the community. By mapping the informal recyclers' routes the project helped to establish 'a sense of identity for the cooperative, providing tangible evidence of their place in the city' (Offenhuber et al., 2012; Offenhuber and Lee, 2012).

1.4 Tangibles

Technology can play an important role in engaging stakeholders. Technology can help stakeholders collect data, collaboratively design and develop scientific models, and explore scenarios. Tangibles – technologies that interactively, physically manifest the digital – are designed to make

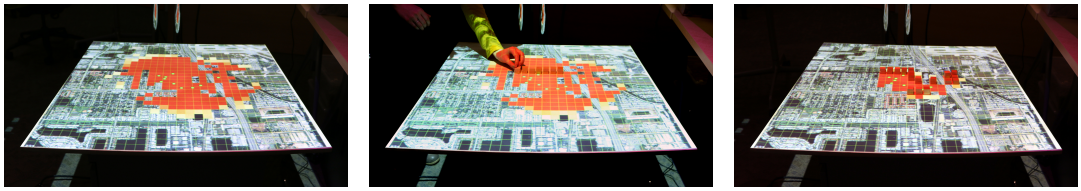

Figure 1: Serious gaming with Tangible Landscape: the termite spread game

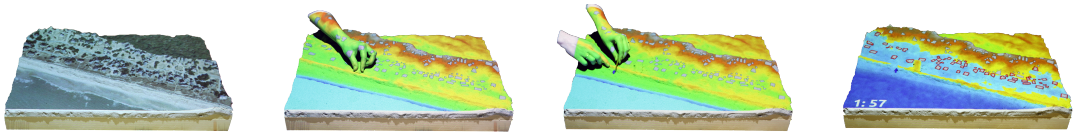

Figure 2: Serious gaming with Tangible Landscape: the coastal flooding game

interaction with computers more natural and intuitive. Tangibles could make technology much more accessible to stakeholders with limited or no experience with computers. Tangible programming (Horn and Jacob, 2007) could potentially be used to engage stakeholders more deeply in the development of scientific models. Tangible interfaces for geographic information systems like Tangible Landscape (Petrasova et al., 2015) could, theoretically, enable stakeholders to naturally interact with complex geospatial models and simulations in order to develop and explore scenarios without any computer experience.

A tangible interface using familiar, everyday materials in everyday ways should be natural to interact with because it leverages existing sensorimotor schemas. When interactions are analogous to everyday tasks the user subconsciously knows what to do and how to do it. In tangibles materiality – the feel, look, and physics – of the media used matters. The choice of material can afford different interactions and mediate meaning, emotion, and motivation.

We hosted a participatory modeling workshop using Tangible Landscape as part of North Carolina State University Library's Coffee & Viz series (Harmon et al., 2016). In this interactive seminar participants explored complex environmental problems by playing serious games. In the games participants used simple tangible interactions to computationally steer simulations, to drive simulated environmental processes. In one game participants managed the spread of termites across a city by treating city blocks. To treat a city block they placed wooden cubes representing preventive treatments on the game board leveraging basic motor skills from childhood play (Fig. 1). In the other game participants tried to save houses from coastal flooding by building coastal defenses. To build defenses they sculpted dunes out of polymeric sand again leveraging motor skills from childhood play (Fig. 2). Participants were able to naturally interact with a statistical epidemiological model and a flood simulation. Because the interactions were so simple they were able to iteratively explore the behavior of multidimensional environmental processes unfolding in time and space.

1.5 Understanding environmental processes

Physical processes like the flow and dispersion of water are challenging to understand because they unfold in time and space, are historically contingent, are controlled by their context, and are driven by forces like gravity and momentum. The flow of water across a landscape is controlled by the morphological shape and gradient of the terrain. It is challenging to understand how water will flow across a landscape because one must not only understand how the shape and gradient of the terrain control the flow and dispersion of water locally, but also how water will flow between shapes and gradients – how the morphology is topologically connected. Understanding a physical process requires thinking at and across multiple spatial scales simultaneously.

Theoretically tangible interfaces for geographic information systems should help users understand environmental processes by giving multidimensional data an interactive, physical form and by graphically and sometimes even physically animating time so that users can explore temporal evolution and scale.

With a physical model one can feel and cognitively grasp a range, albeit a limited range, of spatial scales – scales ranging from what a fingertip can touch, what a hand can grasp, what a body can reach; the relationships between spatial scales within this range of motion should be naturally, subconsciously understood. Situating the spatial scale of a physical model – understanding how its modeled space relates to oneself, to experienced reality – requires a reference, a common datum. Many natural features like topography (Pelletier and Turcotte, 1996), rivers (Rodriguez-Iturbe et al., 1994; Tarboton et al., 1988), and coastlines (Mandelbrot, 1967) have fractal structures, are statistically self-similar, and are scale invariant over a range of spatial scales. This can make it challenging to even approximately judge spatial scale from geographic features. Features of the built environment like houses, however, can be used to approximately judge scale using ones mental model of the feature as a reference. Scales bars and scale rulers are commonly used to more precisely evaluate scale in maps, but are less useful with 3D physical models because it is challenging to read curvature, judge distance, and approximate size visually (Howard, 2012a,b; Jeannerod, 1997) and it is challenging to measure complex surfaces.

Renderings such as perspective views of modeled landscape can help one imagine oneself in the landscape contextualizing the space, relating it to personal experience, and establishing relationships between the scale of the model and the scale of ones body. One can immerse oneself in the modeled landscape with stereoscopic 3D renderings using immersive technologies like virtual reality headsets or cave automatic virtual environments. While this may help one more richly experience the landscape there is the risk of the 'uncanny valley,' the cognitive dissonance when some aspects of the rendering look real, yet others look abstract (Cafaro et al., 2014). While renderings and immersive environments may help situate and contextualize the model they would generate such rich streams of information that it may be challenging to focus on what is most useful at given moment. How can we limited our attention and select the most useful streams of information?

Shape displays – tangible interfaces that physically represent surfaces or volumes like topography – couple a physical model with a digital model enabling users to kinaesthetically and computationally explore space. Continuous shape displays like Tangible Landscape precisely represent continuous surfaces or volumes, but are not scaleable. Dynamic, actuated shape displays like Relief (Leithinger and Ishii, 2010) are scaleable – dynamically reconfiguring topography as one zooms

across scales – and physically animated, but discretely represent surfaces with 3D cells. The resolution of the surface, constrained by the mechanics of the actuators, cannot be high enough to give the impression of a continuous surface. Continuity is important because it links spatial scales. With continuous surfaces one can simultaneously think across spatial scales and potentially understand the topological connection between shapes. With continuous surfaces one can simultaneously think across spatial scales. One can see and feel the topological connection between shapes, potentially understanding the relationship between two spatial scales. Continuous shape displays could be physically animated using robotic fabrication. The physical model could be dynamically reshaped by a robot using additive processes, subtractive processes, or casting. A dynamic, continuous shape display would physically, interactively animate time and space in high resolution so that complex processes can be intuitively grasped.

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1 Point clouds

Point clouds are data structures that represent multidimensional space as an array of coordinates. 3-dimensional (3D) point clouds represent 3D space as an array of x, y, and z coordinates. More coordinates can add to point clouds to represent other dimensions of data such as time, color, or value. 3D point clouds can be generated algorithmically or captured by sensing technologies like lidar, structured light, time-of-flight, or structure from motion. Point clouds captured by these sensing technologies represent sampling points on the sensed surface. Point clouds are used in diverse applications including surveying, spatial modeling, digital fabrication, robotics, and human-computer interaction. Point clouds are used often in tangible interfaces, a type of human-computer interaction that aims to physically manifest digital data – to digitally model physical objects, coupling them with their digital counterparts.

Tangible Landscape – a tangible interface for geographic information systems (GIS) – uses a 3D sensor to capture a physical model of a landscape as a point cloud and import it into GIS. Tangible Landscape's predecessor, the Tangible Geospatial Modeling System, used a terrestrial lidar scanner (Tateosian et al., 2010), the first generation of Tangible Landscape used the first generation Kinect with structured light sensing (Petrasova et al., 2014), and the second generation of Tangible Landscape used the second generation Kinect with time-of-flight sensing (Petrasova et al., 2015). Tangible Landscape couples the physical model with a digital model through a near real-time cycle of 3D scanning, point cloud processing, geospatial modeling and simulation, and projection. This enables users to tangibly interact with digital models and simulations either by shaping topography with their hands or by placing markers that are identified through object detection. As the digital models and simulations update the results are projected back onto the model for the user to see. Tangible Landscape also uses 3D data derived from airborne lidar point clouds as reference data. In either case the point clouds are converted into raster data for geospatial modeling, analysis, and simulation.

1.1 Acquisition

Lidar In lidar sensing the time a pulse of light takes to travel from the sensor and reflect back is used to measure 3D space. A laser, a pulse of light is emitted from the sensor, travels until it hits an object and is reflected back to the sensor. The distance travelled by the pulse is computed from its travel time. The position of the scanned object is computed from the distance travelled by the pulse and the position and orientation of the sensor. The position of the scanned object is recorded as a 3D point. A lidar survey generates a set of 3D points – a point cloud.

Terrestrial lidar can be used to scan small objects or survey landscapes. Turntables are often used to precisely 3D scan all around small objects and capture all of the geometry. Terrestrial lidar surveys can precisely capture features in a landscape at centimeter to millimeter resolution – Starek et al., for example, surveyed gullies at 1 cm resolution from 12 m range (2013). Terrestrial surveys of entire landscapes, however, tend to have highly spatially variable densities with sparse and dense regions due to obstacles and the dispersion of points throughout the field of view.

Entire landscapes can be precisely 3D scanned as point clouds with airborne lidar at meter resolution. As pulses of light are emitted from the aircraft they hit and reflect back from vegetation, struc-

tures, and topography. When a pulse of light hits a tree part of the light is reflected and recorded as the first return, while the rest penetrates the outer canopy. The residual pulse, recorded as a series of returns, reflects off of leaves, branches, shrubs, and the ground. The waveform of the pulse can also be recorded to model the structure of the canopy.

Structured light Structured light – the deformation of a known pattern of light over a surface – can be used to reconstructed 3D depth. Structured light depth sensors like the first generation Kinect project a known pattern of infrared (IR) light onto a scene or object while scanning the scene with an IR sensor to capture the deformation of the pattern of IR light. The depth of the scene can be interpolated from the deformation of the pattern. Structured light depth sensing suffers from data loss – holes in the reconstruction – at the boundary of objects and with transparent or specular materials (Hansard et al., 2013). The first generation Kinect combines an IR projector, an IR sensor, and a color sensor to generate IR amplitude, depth, and color images (Smisek et al., 2011; Hansard et al., 2013). The maximum resolution of the depth image is 640×480 pixels. The first generation Kinect can capture depth images at 0.8 - 3.5 m range with 3 mm xy resolution and 10 mm z resolution at a 2 m distance.

Time-of-flight In time-of-flight depth sensing the phase delay between projected and reflected IR light is used compute depth (Hansard et al., 2013). The second generation Kinect uses a time-of-flight depth sensor with a range of 0.8 - 4.2 m, a maximum depth resolution of 512 × 424 pixels, and a frame rate of 30 frames per second (Bamji et al., 2015). Time-of-flight depth sensing suffers from data drift – offsets in depth values – at the boundary of objects and with transparent materials and from data loss with specular materials. The geometry, color, and material of the scene or object cause variations in the phase and amplitude of reflected IR light giving rise to errors. Systematic errors include noise caused by short integration times and ambiguity caused by variations in amplitude due to color. Non-systematic errors include motion blur and scattering caused by IR saturation, ambiguous borders, and overlapping reflected IR signals (Hansard et al., 2013).

Structure from motion In structure from motion 3D surfaces are algorithmically reconstructed by matching features captured from multiple viewpoints in overlapping, offset images. Image matching algorithms match features in random, unstructured sets of photographs with enough overlapping images. Bundle adjustment is then used to optimize the camera parameters and the geometry of the surface (Westoby et al., 2012; Fonstad et al., 2013; Snavely et al., 2008).

Structure from motion can be used to reconstruct DEMs from aerial photography captured by manned or unmanned aerial vehicles (UAVs). Structure from motion for aerial photography generates a 3D point cloud from matched features that can be georeferenced using ground control points or the recorded position of the camera (Fonstad et al., 2013).

The resolution of the point cloud depends upon the height of the aircraft, the resolution of the camera, and the percent overlap of the photographs. Imagery from low altitude aircraft like UAVs can be used to generate high resolution point clouds – for example imagery captured by a UAV flying at an altitude of 120 m with a 2456 x 1632 pixel resolution camera can generate a 10 cm resolution point cloud.

1.2 Modeling

Once a point cloud has been captured it can be used to generate other 3D representations such as meshes, parametric surfaces and volumes, 2.5D rasters, and 3D rasters. 2.5D rasters are xy arrays of cells with a z value representing elevation, whereas 3D rasters are xyz arrays of volumetric cells that can have a value representing a 4th dimension of data.

Raster representations of landscapes such as digital elevation models (DEMs) – rasters representing bare earth topography – and digital surface models (DSMs) – rasters representing topography, vegetation, and structures – are commonly used in GIS to model and analyze terrain because they can easily be mathematically transformed. The partial derivatives of a function approximating a DEM or DSM, for example, can be used to compute topographic parameters such as slope, aspect, and curvature.

Point clouds representing landscapes captured by 3D sensing technologies like structure from motion and time-of-flight require processing before they can be modeled as DEMs or DSMs. Outlying points should be filtered and the data should be georeferenced. Sometimes edge detection can be used to identify boundaries and extract a region.

Lidar point clouds stored in the las format can be filtered by returns and, if classified, by classes. They can be filtered by the first return, middle return, or last return. They can also be filtered by the following classes: 0 for created,1 for unclassified, 2 for ground, 3 for low vegetation 4 for medium vegetation, 5 for high vegetation, 6 for building, 7 for low point, 8 for model key-point, 9 for water, 10 for reserved, 11 for reserved. 12 for overlap, and 13-31 for reserved (ASPRS, 2013).

Unclassified point clouds – whether from lidar or other 3D sensing technologies like structure from motion and time-of-flight – can be automatically classified. Edge detection can be used to identify and classify features like buildings. Ground points can be automatically classified using the multi-scale curvature classification algorithm, 'an iterative multiscale algorithm for classifying LiDAR returns that exceed positive surface curvature thresholds' (Evans and Hudak, 2007).

Point clouds should be filtered before being used to generate DEMs or DSMs. Only points classified as ground should be used to model bare earth topography as a DEM. Only the first return and classes 1,2,3,4,5,6,9 should be used to model topography, vegetation, and buildings as a DSM.

Raster surfaces like DEMs and DSMs can be computed from point clouds using either binning or interpolation. In binning values are assigned to cells based on a univariate statistical analysis of the z coordinates of the set of points contained in the cell. Statistical methods for computing raster values from a set of points include sample size (n), minimum, maximum, range, sum, mean, standard deviation, variance, the coefficient of variance, median, and percentile. Binning is a fast method, but can result in rough surfaces with holes in regions without enough points.

In interpolation the values between points are estimated mathematically or statistically. Interpolation can be processing intensive, but can fill holes in data and – with the right choice of method and parameters – can smoothly, precisely model complex surfaces. Poorly parameterized methods can cause distortions like overfitting (with overshooting and pitting) or over smoothing. Methods include kriging, radial basis function, natural neighbor, inverse weighted distance, bicubic spline, and regularized spline with tension interpolation.

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1 Tangible interfaces for Geographic Information Systems

Coupling physical models with GIS In a seminal paper Ishii and Ullmer envisioned tangible user interfaces that would 'bridge the gap between cyberspace and the physical environment by making digital information (bits) tangible' (1997). They described 'tangible bits' as 'the coupling of bits with graspable physical objects' (Ishii and Ullmer, 1997). Tangible interfaces like Urp (Underkoffler and Ishii, 1999), Illuminating Clay (Piper et al., 2002), and SandScape (Ratti et al., 2004) enriched physical models of urban spaces and landscapes with spatial analyses and simulations like wind direction, cast shadow, slope, aspect, curvature, and water direction in order to enhance and streamline design processes. Many of the analyses used in Illuminating Clay were adapted from GRASS GIS (Piper et al., 2002). and eventually Illuminating Clay was coupled with GRASS GIS to draw on its extensive libraries for spatial compuation. The aim of coupling Illuminating Clay with GRASS GIS was to 'explore relationships that occur between different terrains, the physical parameters of terrains, and the landscape processes that occur in these terrains' (Mitasova et al., 2006). This research to couple a physical landscape model with GRASS GIS led to the development of the Tangible Geospatial Modeling System (Tateosian et al., 2010) and Tangible Landscape (Petrasova et al., 2014, 2015).

There are many reasons for coupling a physical model with a GIS – for developing a tangible interface for a GIS. The tangible interface enables intuitive digital sculpting, streamlines design processes by seamlessly integrating analog and digital workflows, and improves collaboration and communication by enabling multiple users to simultaneously interact in a natural way (Ratti et al., 2004). The GIS provides the extensive libraries for geospatial databasing, processing, analysis, modeling, simulation, and visualization needed to address real world problems (Tateosian et al., 2010). A tangible interface for a GIS that enables intuitive digital sculpting while providing analytical or simulated feedback would allow users to dynamically explore how topographic form influences landscape processes (Mitasova et al., 2006).

To couple a physical model with a GIS the physical model needs to be digitized and imported into the GIS and then models, analyses, and simulations need to be output as feedback. Once a physical model has been 3D scanned as a point cloud it can be imported into GIS. GIS functionality for handling tangible input could include georeferencing, point cloud processing and importing, binning or interpolation, and object detection. Once the tangible input has been imported into GIS it can be used in geospatial models, analyses, and simulations. GIS have extensive libraries for geospatial modeling, analysis, and simulation including statistical analysis, terrain modeling, terrain analysis (including slope, aspect, curvature, and landform recognition), cut-fill analysis, volumetric modeling, time series analysis, solar irradiation modeling, hydrological modeling, water flow simulation, sediment flow and erosion simulation, landscape fragmentation analysis, landscape change modeling, least cost path analysis, and network analysis and optimization. These libraries support landscape planning applications including stormwater management, flood control, landscape management and erosion control, trail planning, viewshed analysis and visual impact assessment, and the assessment of solar potential. They also support landscape change applications including wildfire management, disease spread management, urban growth, and sea level rise adaption. GIS also have libraries for visualization including 2D and 3D cartographic rendering, graphs, and animation that enable graphical feedback.

Challenges and future work Theoretically Tangible Landscape should enable natural and collaborative interaction with a GIS by coupling physical and digital geospatial models. Natural interaction with geospatial models should enhance spatial cognition and encourage spatial learning. This should be empirically tested in experiments and case studies so that we can critique and develop the theory grounding Tangible Landscape, identify cognitive challenges, and improve the design.

Tangible Landscape's physical model, augmented with projected graphics, only affords a bird's eye view of the modeled landscape. With a bird's eye view of a scale model one can not get a sense of how the landscape would look when one is there. While 3D renderings can show how the landscape would look from a viewpoint, immersive technologies could give a richer impression of the space. Virtual reality headsets with interactive 3D scenes could be integrated with Tangible Landscape so that users can explore and experience the modeled landscape at a human scale.

Tangible interfaces like Tangible Landscape have two feedback loops – there is passive, kinaesthetic feedback from grasping the physical model and active, graphical feedback from computation. This double interaction loop could be enriched by a third form of feedback, by computationally transforming the physical model for active, kinaesthetic feedback (Ishii, 2008). While there is ongoing research into actuated shape-changing displays like Relief (Leithinger and Ishii, 2010), they are expensive to build and maintain and the size of the actuators limits the spatial resolution making the surface discrete rather than continuous. I instead propose to integrate robotic fabrication technologies into Tangible Landscape in order to computationally transform the physical model with high precision. A robot mounted beside Tangible Landscape could precisely manufacture changes to the physical model using computer numerical control milling, 3D printing, and casting based on geospatial modeling and simulation. While it would take substantial time to fabricate new models using digital fabrication technologies, small changes could be made in near real-time.

Digital fabrication technologies could also couple Tangible Landscape with the real world landscape being modeling. Live, real-time data about the landscape could be collected and streamed from sources like UAV flights, lidar stations, monitoring stations, and embedded sensors. With this streaming data the robot mounted beside Tangible Landscape could automatically transform the physical model representing the landscape in near real-time response to changes in the landscape. This would give us a live, tangible representation of a landscape that could help us to understand its processes and support near real-time decision making. Tangible Landscape could also be integrated with digital fabrication in the field – with computationally driven, location-aware earthmovers – to directly transform the landscape being modeled.

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