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ORIGINAL ARTICLE

Overcoming barriers to sustainability by combining conceptual, visual, and networking systems

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Abstract
Sustainability challenges rarely align with the conventional boundaries of our disciplines, institutions and means of communication. To address these challenges amid real-world complexity, we need to think holistically and collaborate across disciplines. In this paper, we synthesise three themes: (1) more *integrated conceptual frameworks*; (2) digital *visual communication* which provides fluid expression of complex ideas and perceptions; and (3) *online networks* which can empower sustainability initiatives and communicate them across social and institutional barriers at a global scale. Each of these tools can help to overcome persistent barriers to sustainability. When used together, they provide a strategic basis for the design of digital collaboration platforms for addressing sustainability challenges. Using design thinking, we developed a Synergy Map which identifies relationships among a number of barriers to sustainability and conceptual and digital tools which help to address them. The Map identifies the potential for synthesising these tools into effective digital artefacts. We provide several examples and identify characteristics of particular value for overcoming barriers to sustainability. Combining new theoretical developments in sustainability sciences with recent advances in communication and networking technologies offers substantial potential for advancing sustainability on multiple fronts.

Keywords Conceptual frameworks · Design thinking · Interdisciplinary collaboration · Online networks · Sustainability · Visual communication

Introduction

Progress towards achieving a more sustainable future is slow. This is partly because the way we have historically thought and communicated about sustainability is unsuited to the complex nature of sustainability problems (Sterling 2009). Many sustainability issues are transdisciplinary (Hadorn et al. 2008), context-dependent, rapidly evolving and socially mediated (Rittel and Webber 1973). In contrast, traditional ways of thinking are narrow in scope and reductionist, obscuring important relationships (Siebert 2011; Sterling 2009). This approach may be suitable for solving discrete problems, but is unable to deal with complex sustainability issues (Bennett et al. 2009; Nassauer and Opdam 2008). The conceptual challenges are compounded by entrenched disciplinary silos (Becher and Trowler 1989) and divisions among scholars, leaders and citizens (Hadorn et al. 2008). There is a pressing need for more effective systems of communication and knowledge exchange if we are to overcome these challenges (Miller et al. 2014).

How we understand and communicate sustainability are interrelated (Beddoe et al. 2009; McGreavy et al. 2015). The written and spoken words on which we heavily rely are linear and insufficient for communicating the complexity of sustainability problems and their solutions (Siebert 2011). This limits both our thinking, and our ability to communicate effectively across disciplines and with policy makers and the broader community. Developing and implementing effective strategies for achieving sustainability goals requires an integrated understanding of different facets of our

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social–ecological system (Brandt et al. 2013). This requires a common language which can express the interdependent relationships, multiple perspectives and shifting scales which arise in social–ecological systems (Stibbe 2009; Glandon 2015).

Advances in sustainability theory from a number of fields pave the way for a more comprehensive conceptualisation of environmental problems (Berkes and Ross 2013; Brown 2007; Lang et al. 2012; Miller et al. 2014). These newer conceptual frameworks—such as social–ecological systems, resilience, planetary boundaries and ecosystem services—help to guide enquiry and provide a foundation for stronger collaboration across disciplines (Heemskerk et al. 2003). Due to their complex and non-linear nature, many of these conceptual frameworks are expressed and manipulated most effectively through digital media (Mann 2011). Advances in digital media provide two powerful new tools: interactive visual communication, and online collaboration networks. Visual communication methods—such as data visualisation, concept mapping and dynamic multi-media—aid the fluid expression of complex ideas and relationships (Heinrichs 2011; Throsby 2014). At the same time, online networks offer unprecedented potential to expand the dialogue on sustainability across social barriers and reconnect knowledge with action (Godemann and Michelsen 2011b; Kelly 1998; Newig 2011). In addition, these tools possess substantial potential for mutual support as they are most effective when their components are synthesised into powerful communication tools. However, there has been limited application of these tools, and their considerable potential remains untapped. Currently, no platforms exist which use digital visualisation and networking technologies to communicate integrated multidisciplinary frameworks of sustainability. To advance the understanding and resolution of sustainability issues, new tools and approaches are needed for communicating their multi-dimensional nature.

In this paper, we first introduce the Synergy Map—a concept map which guides thinking on how conceptual and digital tools may help overcome several barriers to sustainability by improving the way we think, communicate and collaborate. Second, we examine the utility of three tools currently undergoing rapid development: (1) integrated conceptual frameworks; (2) visual communication systems; and (3) large-scale, online communication networks. While the component principles are well established across diverse disciplines, we integrate them here for the first time. Finally, we discuss the synergy and challenges involved in combining these tools into a digital collaboration platform to help achieve sustainability goals (Maher 2017).

The synergy map

What it is and why?

The complex relationships among barriers to sustainability and tools to help address them are usually explored in isolation. However, to design effective initiatives, we need to understand how they relate and where there is synergy between them. To visualise these relationships, we developed the Synergy Map (Fig. 1). It represents a synthesis of a targeted multidisciplinary literature review and provides a strategic basis for the design of systems for collaboration. Throughout this paper, terms in *italics* appear in Fig. 1.

The Synergy Map has three components which establish the synergetic relationships among *barriers* to sustainability, *tools* that may help to address them, and *potential digital artefacts* built from their synthesis. The multiple overlapping interdependencies among these components are non-linear and diagrams describe them far more clearly than written text. In Fig. 1, each section contains a number of issues with arrows representing relationships between two elements as identified in the literature. While many scholars examine how a particular strategy or tool can address a particular barrier to sustainability, we focus on their multi-dimensional relationships to reveal the potential of each tool to concurrently address several barriers to sustainability and provide mutual support. The content of the Synergy Map is by no means exhaustive. There are many other barriers to sustainability, but those included here are related by their potential to be addressed by combining these conceptual and digital communication tools.

Approach: research through design

Design thinking is particularly well-suited to developing integrated solutions to wicked problems (Glanville 2007; Zimmerman et al. 2010). Glanville, a design and systems theorist describes how "Designers handle, on a daily basis, incalculably complex (and ambiguously defined) problems, bringing them to simple resolution: designers typically make one object that satisfies a myriad of often contradictory and ill-defined requirements" (Ranulph Glanville 2007, p. 75). To do this, design applies a fundamentally different approach to generating knowledge to the sciences (Kolko 2009) and requires a different approach to research (Faste and Faste 2012; Zimmerman et al. 2007, 2010). In particular, "...while typical research tends to have the goal of narrowing its focus towards specific solutions to well-defined problems, design research often results in a broadened understanding of the problem domain and [identifying] many alternative potential solutions" (Faste and Faste 2012). In this case, we applied design thinking to explore opportunities to address barriers to sustainability through new theory and digital

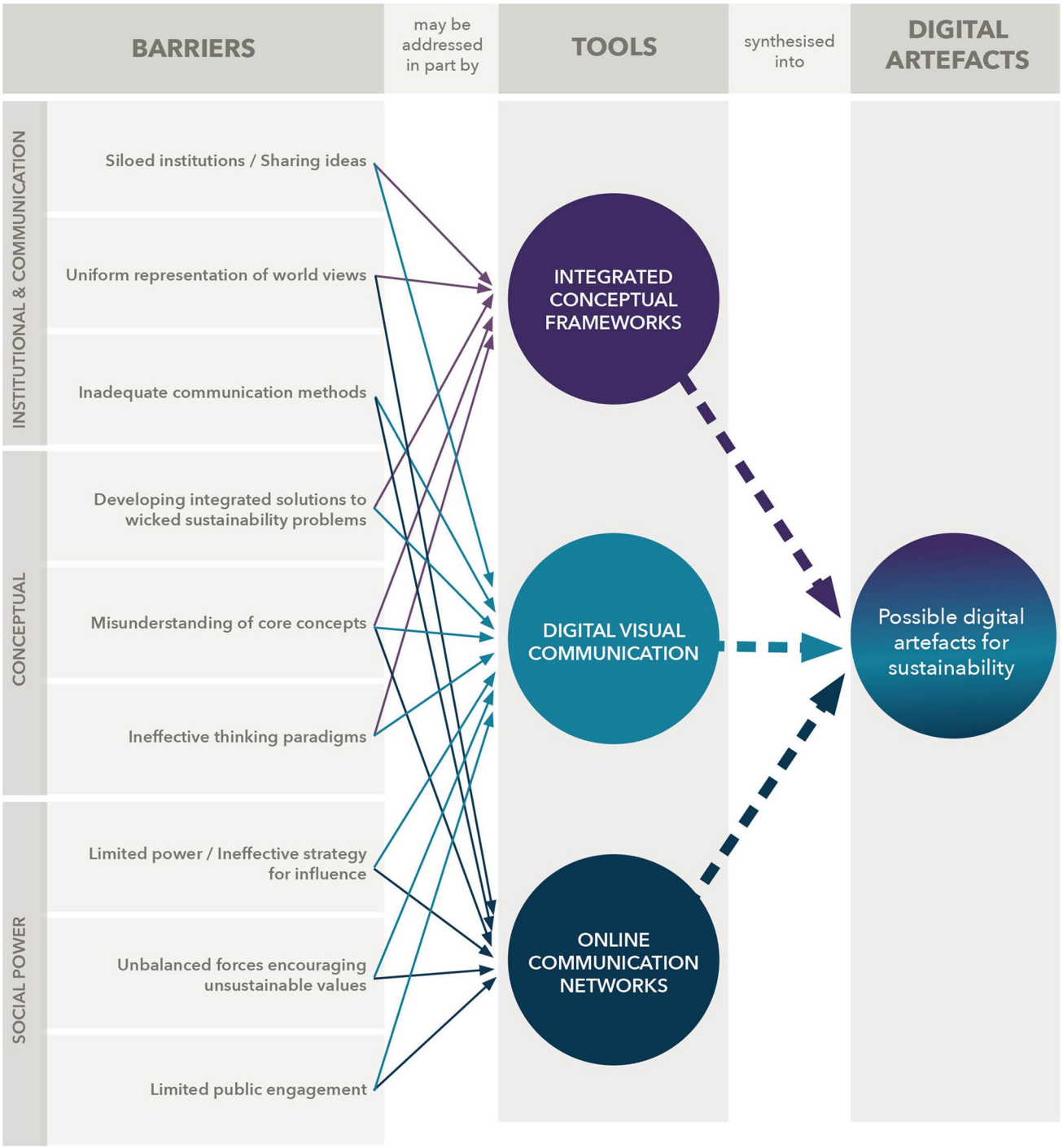

Fig. 1 Synergy Map describing relationships among critical barriers to sustainability, tools to help address them and their potential for synthesis into effective digital artefacts for sustainability. Each arrow represents a relationship between two elements as identified in the literature. Following any path from left to right describes how a particular barrier may be addressed in part by applying a particular tool which may form part of a digital artefact. Reading from right to left describes how a digital artefact created from a synthesis of the three tools may help to address several persistent barriers to sustainability

media. A typical research approach may be to focus exclusively on one barrier and develop a single, optimal solution. However, barriers to sustainability and their potential solutions are complex and highly interdependent. Trying to solve any one problem in isolation will likely be ineffective and inefficient, leading to a division of resources and missing out on potential synergy between strategies (Glanville 2007). Instead, by understanding how different barriers to

advancing sustainability are interrelated, we can develop responses which help to address them simultaneously and with mutual support. This 'synergy' is the basis of effective design outcomes (Faste and Faste 2012; Glanville 2007; Zimmerman et al. 2010).

Research through Design is a research methodology which applies methods, attitudes and processes from design practice to address complex and vaguely defined research challenges (Rodgers and Yee 2014; Kennedy-Clark 2013). While these methods are unsuited to quantitative data analysis, they excel at reframing problems and opportunities (Hevner 2007), synthesising apparently conflicting perspectives and creating well-integrated outcomes that are fit for their social/ecological/technological context (Moloney 2015). We applied a number of Research through Design methods to create the Synergy Map. First, we used visual concept mapping to synthesise a targeted, multidisciplinary literature review. The review focused on scholarly contributions from a range of disciplines to inform the design of digital artefacts for sustainability. This included reviewing core concepts and approaches from multiple disciplines: sustainability sciences (e.g., Miller et al. 2014), landscape ecology (e.g., Wu 2013), design (e.g., Glanville 2007), sustainability communication (e.g., Godemann and Michelsen 2011a), collective intelligence (e.g., Malone et al. 2010), human–computer interface (HCI) (e.g., Blevis 2007; Zimmerman et al. 2007), integral theory (e.g., Brown and Riedy 2006), environmental sociology (e.g., ISSC and UNESCO 2013), and strategy (e.g., Patel 2005; Broman and Robert 2017) among others. Seeking actionable outcomes, we limited the review to identifying core issues and how they may inform design. The aim was to identify, understand and synthesise a broad spectrum of barriers to sustainability and the strategies, approaches, conceptual frameworks and digital tools that are being employed to help address them. It is not intended to be an exhaustive systematic review, rather a sampling that suggests a tool for synthesis would be useful—indeed a tool for synthesis could in future support such a systematic review. The synthesis helped to identify new avenues for inquiry as it developed so specific review criteria could not be predetermined. This iterative approach is common in Research through Design (Rodgers and Yee 2014).

We applied soft systems methodology using concept mapping tools (Cañas et al. 2004) to synthesise the literature and identify common themes and relationships. Soft systems methodology is an "action-oriented process of inquiry into problematic situations…using models…as intellectual devices" (Checkland and Poulter 2010). Manipulating these concept maps and other 'sensemaking' processes (Kolko 2009) helped to reframe isolated ideas into a broader synthesis. Analysing existing digital artefacts for sustainability also contributed to the Synergy Map (See Tables 1, 2, 3 for examples). The process was iterative and is summarised below and in Fig. 2 as follows (the numbers refer to the different stages in Fig. 2):

1. Relevant issues from some of the literature were mapped in Cmap Tools (Checkland and Poulter 2010). Nodes represent concepts and links show relations between them.

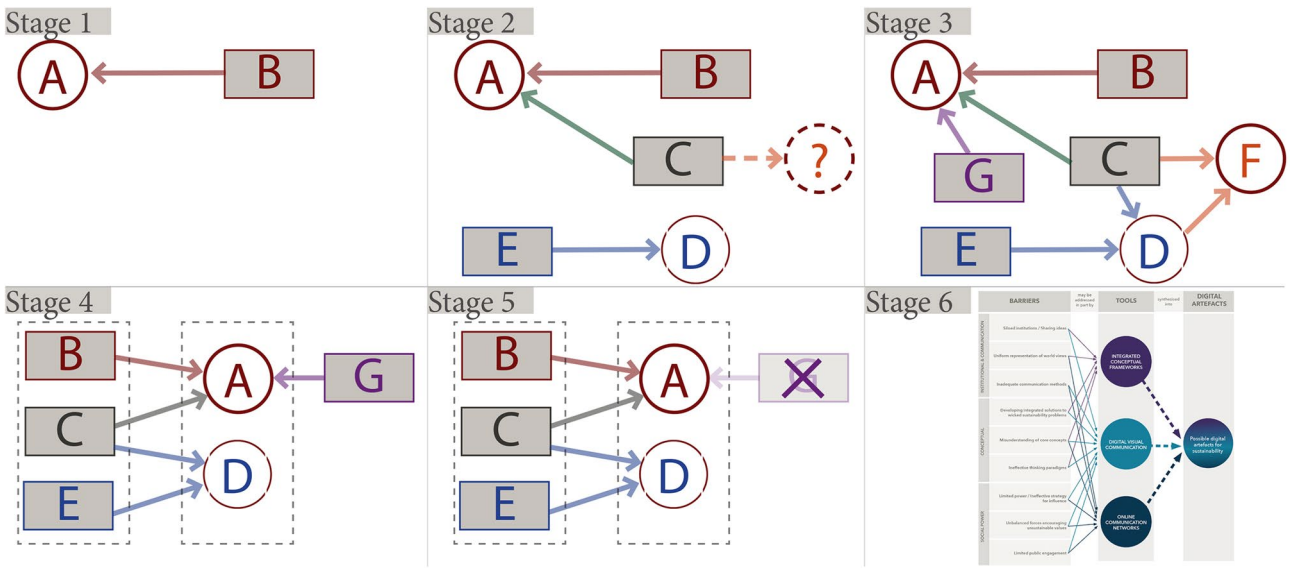

Fig. 2 Sequential diagram describing the evolution of Synergy Map. Core themes from diverse literature and precedents are represented as nodes and links. Letters A–G represent prominent themes in the literature. Arrows show relationships among them. Each colour represents a different set of literature. These were synthesised through several stages into a concept map to inform the design of digital artefacts for sustainability. Throughout this process, the concept map developed from simple to complex and from messy to organised. The six steps are described in the main text

2. Other concepts and relations from different authors and disciplines were added and linked to existing content. Identifying patterns visually helped to identify fruitful avenues of inquiry in related disciplines.
3. Adding points of overlap allowed a system map to emerge.
4. We reorganised the system map repeatedly to help identify themes and groups.
5. We excluded concepts which were not well integrated.
6. The Synergy Map was developed, which was used to inform the design of a digital collaboration platform for sustainability as outlined below (Text box 3; Fig. 4) (Maher et al. 2018).

Overall findings

The review and synthesis found that combining (1) *integrated conceptual frameworks*, (2) *visual communication*, and (3) *online communication networks* could provide a strong basis for the design of digital artefacts to advance sustainability. Based on these outcomes, a digital artefact could be designed to contain multiple overlapping strategies for helping to address several persistent barriers to sustainability.

We now expand on each component of the Synergy Map in turn, beginning by exploring some of the persistent barriers to advancing sustainability and how they are interrelated.

Throughout this paper, terms in *italics* appear in Fig. 1.

Barriers

Several aspects of our social system (e.g., thinking paradigms and divisions among disciplines) make it more difficult to advance understanding and action on sustainability. Several of these aspects are represented in Fig. 1 and relate to institutional and communication barriers, conceptual barriers and social power barriers. Here, we describe a number of the key barriers before examining how conceptual and digital tools can help to address them.

Institutional, communication and conceptual barriers

Our over-reliance on reductionist thinking reinforces artificial boundaries between cultural values, infrastructure, ecosystems and the services they provide (Abson et al. 2014; Wayman and John 2009). This has led to many institutions that have little correlation with the relationships found in nature and society (Guerrero et al. 2015). The ensuing segregation of people and knowledge makes solving sustainability issues conceptually challenging (where concepts and terminology become self-referential and highly specialised) and socially (where individuals rarely communicate across institutional boundaries). These conceptual and social barriers combine to restrict the synthesis and integration of sustainability concepts across disciplines. The siloed nature of research and governance institutions (Hadorn et al. 2008; Sengers and Gaver 2006) has led to disconnected concepts of sustainability (Sterling 2009) and the inefficient application of projects and policies (Strackan 2009; Wells 2012). Lacking a strong interdisciplinary dialogue, many sustainability initiatives suffer from uniform representation of world views (Henry and Pene 2001). Interdisciplinary knowledge sharing is critical for identifying ingrained contradictions of sustainability disciplines and promoting new conceptual developments (Hadorn et al. 2008). While a growing number of researchers engage in transdisciplinary research (Strackan 2009), progress is hampered by a lack of coherent framing of sustainability challenges and shared terminology (Brandt et al. 2013).

Sustainability brings a host of unprecedented communication challenges. Many sustainability issues are invisible, distant, uncertain, and abstract in nature (Moser 2010). These are compounded by the inaccessibility of academic research (Heinrichs 2011). Together, this makes it difficult to communicate the complexity of challenges and develop collaborative solutions. However, communication includes not just facts and concepts but also values, ambitions and motivations. Without communication which is clear, engaging and persuasive, many core sustainability concepts will continue to be misunderstood by decision makers, scholars and citizens (Stibbe 2009). This undermines problem recognition and change in institutions, societal values and the built environment.

Social power barriers

There is an emerging shift in sustainability research from describing the world to transforming it (McAlpine et al. 2015; Miller et al. 2014). The sustainability community has made advances in growing and directing social, economic and political influence, but slow progress reveals both the shortcomings in our current approach and also the enormous complexity of the problems we face. This is in part due to the limited power of sustainability groups, in comparison to rival interests with a dominant media presence (Blewitt 2009; Chomsky 1993). Ineffective strategic thinking and unpersuasive forms of communication further compound this issue (Siebert 2011). The same institutional siloes which restrict the synthesis of knowledge also inhibit advocates of sustainability from forming influential social coalitions (Tegmark 2012).

There have been consistent and growing calls for increased public participation in sustainability issues (Dodds et al. 2012; Kelly 1998), but numerous barriers restrict participation. These include hierarchical power structures where citizen's voices are actively repressed

(Evans 2012; Newig 2011), and the inability to access or make sense of information (Kruse 2011). Few sustainability experts have the skills or resources to apply persuasive communication, and so fail to engage the public (Adomßent and Godemann 2011). Fewer still effectively link knowledge to local actions in a readily accessible manner (Adomßent and Godemann 2011; Wayman and John 2009). This creates an imbalance of forces that encourage unsustainable social values (Goldberg 2009). To facilitate genuine participation, we must address a number of significant barriers such as the complexity of many sustainability issues, the hierarchical structure of institutions and inadequate application of communication strategies (Blewitt 2009; Godemann and Michelsen 2011b; Kruse 2011).

The collective inertia embedded in these barriers substantially impedes progress towards sustainability. However, a common set of conceptual and digital communication tools can help to break down silos, communicate complexity with clarity, sharpen our thinking and extend the social reach of Sustainability Science and advocates (Fig. 1). Next, we expand on these tools.

Three tools for advancing sustainability

The way we shape systems for thinking and communication are central to applying sustainability theory strategically (Patel 2005). Currently, three significant *tools* which help to address these barriers to sustainability are being developed in parallel by researchers and practitioners around the world. These include: (1) *integrated conceptual frameworks* that synthesise diverse concepts and thinking paradigms; (2) state-of-the-art *visual communication* empowered by interactive digital media; and (3) user-powered *online communication networks*. The application of these *tools* for thinking about and communicating sustainability is growing, and a few examples are briefly introduced below. We later show that when combined, each tool may enhance the effectiveness of the others. However, to date there are few examples of their successful integration despite the many common synergies.

Tool 1: integrated conceptual frameworks

Developing more integrated conceptual frameworks of sustainability can help to frame problems, guide thinking, synthesise knowledge and communicate complex issues across social divides (Heemskerk et al. 2003; Mann 2011). Structured conceptual frameworks help shape perception, cognition and communication. This is important for sustainability as "reaching a sustainable society without any idea of the principles that define that situation would be very unlikely" (Broman 2014). *Integrated conceptual frameworks* can help us recognise patterns which might otherwise go unnoticed. For example, the concept of ecosystems literally helps us to 'see the forest for the trees' and uncovers myriad unique processes, interactions and interdependencies (Krebs 1989). Conceptual frameworks are tools to help us think but they are also built on particular world views, depending on the background and experiences of their developers. By revealing some concepts and excluding others they act as a lens through which we perceive the world (Mann 2011).

Considering the complex, interdependent and constantly shifting worlds of human society and nature from a single perspective can only provide a limited understanding. With a narrow view, ideas and methods that are not included in the frame of reference being used are easily overlooked (Sousanis 2015).

Existing conceptual frameworks of sustainability

Several conceptual frameworks are increasingly recognised as core to understanding and responding to sustainability issues (Mann 2011). These form the basis of analytical tools, international agreements or entire fields of research. At a practical level, they provide "…excellent tools for initiating discussions, revealing hidden and unacknowledged assumptions, and identifying areas in which scientists from different fields agreed or disagreed" (Heemskerk et al. 2003). Research synthesising ecological and social sciences is at the forefront of developing integrated conceptual frameworks for sustainability. For example, the concept of Ecosystem Services captures many properties of ecosystems which are valuable to people (Abson et al. 2014). Ecological Footprints (Ewing et al. 2008) and Planetary Boundaries (Rockström et al. 2009) describe limits to consumption and growth of our population and economy. Social–ecological systems frameworks describe phenomena that emerge from interactions between human and nature (Folke 2006). Resilience is used differently by Earth System sciences and Environmental Humanities, but both relate to the ways a system can adapt to change while retaining fundamental characteristics (Berkes and Ross 2013). Collectively, these frameworks provide a strong foundation for research and education in sustainability, but they do have critical limits (Table 1).

Limits of existing frameworks

Despite their relatively inclusive nature, the conceptual frameworks described above focuses on part of the system and excludes concepts and perspectives critical for sustainability. Of these just described, only Ecosystem Services includes ethical orientations and even then, it is entirely anthropocentric. Few express subjective personal experience

Table 1 Potential qualities of conceptual frameworks for sustainability

Quality	Common examples	Barriers it helps to address (all also help to address 'ineffective thinking paradigms')
Integrating natural environment, built environment and society	Ecosystem services (Abson et al. 2014), Net Positive Development (Birkeland 2012)	Siloed institutions Developing integrated solutions to wicked sustainability problems
Systemic (e.g., emergence, resilience)	Planetary boundaries (Rockström et al. 2009)	Siloed institutions
Spanning subjective–objective	Integral theory (Brown, 2007)	Siloed institutions Limited public engagement Developing integrated solutions to wicked sustainability problems Imbalance of forces that encourage unsustainable social values Uniform representation of world views
Flexible boundaries/uncertainty	Design thinking (Glanville, 2007) Systematic boundary critique (Ulrich and Reynolds 2010)	Developing integrated solutions to wicked sustainability problems Limited public engagement
Broad space scales	Ecological footprint (Wackernagel & Rees, 1996)	Misunderstanding of core concepts
Broad time scales	Ecocity framework (Ecocity Builders 2011)	Misunderstanding of core concepts

even though it is how each of us perceive the world. Only a few consider future states and most are descriptive rather than transformative—they seek to objectively describe how the world is rather than deliberately shaping its future. This alone is insufficient for addressing sustainability issues (Brown and Riedy 2006; Miller et al. 2014). To accelerate progress towards sustainability, "systemic knowledge needs to be combined with…ethical orientations towards the relationship between humankind and nature, with direct experiences that involve emotionality and meaningfulness" (Godemann and Michelsen 2011a, p. 9). These subjective aspects are an essential part of our mental models of sustainability as "...our constructs of reality are just as much emotional as cognitive" (Siebert 2011).

Achieving a more comprehensive approach is conceptually challenging, but valuable precedents exist in other fields which have not yet been integrated with the Sustainability Sciences. These include Design Thinking, Symbiosis in Development, Ecological Handprint and Integral Theory. Design Thinking introduces many methods for creating harmonious and context-sensitive solutions to problems which are multi-faceted, vaguely defined and socially contested (Glanville 2007). Symbiosis in Development combines methods and theories from multiple fields for 'developing multi-faceted sustainability innovations' (SymbiosisInDevelopment 2009). Ecological Handprint balances often negative perspectives by highlighting the ways people can have positive impacts on natural systems (Biemer et al. 2013). Integral Theory unites objective, subjective, individual and collective perspectives into a more complete, complementary approach (Brown 2007). This highlights the systemic, cultural, behavioural and psychological dimensions of sustainability, and provides the breadth of scope required for effectively understanding and addressing sustainability problems. Further integration and development of these conceptual frameworks can help to understand how the world works, how it could be, and what we need to do to get there.

Conceptual frameworks are most effectively described with schematic images which we can then 'visualise' in our minds. Different communication methods can limit the complexity, clarity and structure of the framework and hence the quality of our mental representations. Advanced communication methods, greatly improved by digital platforms, can foster the development of more comprehensive conceptual frameworks of sustainability.

Tool 2: visual digital communication

By employing visual communication in digital environments, sustainability ambassadors can expand their ability to clarify, inspire, collaborate and think. Our symbolic systems affect how we perceive, communicate and think about the world (Lester 2006). Written words encode meaning into a sequence of shapes, but this is only a small fraction of the palette of visual communication techniques. Further nuance and complexity can be communicated by articulating colour, size, shape, pattern and composition. Digital platforms expand this palette to include user interaction and movement. By shaping these "skilled visual designers manipulate the perception, cognition, and communicative intent of visualizations..." (Agrawala et al. 2011). This broader spectrum of communication provides a range of qualities which are valuable for helping to address barriers to sustainability (Table 2). For example, Gapminder World uses highly interactive graphs to explore relationships between

Table 2 Potential qualities of visual communication for sustainability

Quality	Common examples	Barriers it helps to address
Accessible	Gapminder (Gapminder 2016)	Siloed institutions Uniform representation of world views Misunderstanding of core concepts
Interactive	Design sketching, concept maps	Ineffective thinking paradigms Developing integrated solutions to wicked sustainability problems
Ambience	Political campaigns	Limited power of sustainability groups Imbalance of forces that encourage unsustainable social values Limited public engagement
Persuasive	Product advertising	Ineffective strategy for directing social, economic and political influence Limited power of sustainability groups Imbalance of forces that encourage unsustainable social values
Describe complex relationships	Foodweb diagram, geographic information systems (Collins 2011)	Inadequate communication methods Ineffective thinking paradigms
Common language	Maps, icons	Siloed institutions Uniform representation of world views
Layers of meaning	Visual arts, architectural drafting	Uniform representation of world views Ineffective thinking paradigms
Optimize intellectual performance	Diagrams, design sketching	Developing integrated solutions to wicked sustainability problems

diverse demographic data (Gapminder 2016). Its interface is accessible and interactive, expressing layers of meaning in a common language. This helps to improve interest and literacy in sustainability.

Visuals shape our thinking

In many aspects of life, visual tools can help us to think in particular ways. For sustainability, they can facilitate complex thinking and sharing complex ideas—essential for developing more comprehensive conceptual frameworks. Visual communication methods each enhance some ways of thinking while suppressing others. For example, while a page of text must be read in a specific order to make sense, an image may be 'read' in several different ways, each revealing a different layer of meaning (Suwa et al. 2001). This makes images especially useful for expressing non-linear relationships and multiple perspectives common to sustainability. Visuals are often used to find meaning in complex data. Well-designed visual aids can even optimize the intellectual performance of users by reducing 'cognitive load'—the work done by our limited short-term memory when solving problems (Dunlosky et al. 2013; Sweller et al. 1998).

Design disciplines typically address problems by manipulating sketches, concept maps and computer models. These interactive visuals are particularly good at facilitating the type of thinking needed to solve sustainability problems: adaptive, non-linear, collaborative and iterative problem solving. As we clarify the ways we need to think to solve sustainability issues, we can design visual tools to enhance them. Many new digital platforms greatly enhance our ability to think by allowing users to manipulate images thus providing rapid feedback for developing ideas and collaborating.

Visuals shape our culture

Communication is not limited to the transfer of knowledge, but also expresses aspirations, values and perspectives on our relationship with future generations and the natural world (Godemann and Michelsen 2011b). Visual communication can provide a common language accessible across disciplines, ages and language groups (Vervoort et al. 2014). Combined with their potential for emotive expression, visuals can help build an inclusive dialogue on sustainability. As such, visual communication provides a medium for cultural evolution, such as these influential images in Fig. 3.

If sustainability advocates wish to transform society (Miller 2013), then digital visual communication is a critical tool. Through marketing and branding, visual communications can help sustainability ideas, values and products command attention in a competitive world. In this endeavour, ambience is as important as information. Digital environments for sustainability can be designed to direct attention, herald authority and inspire action. Many otherwise excellent sustainability initiatives forsake persuasive visual communication and thus fail to inspire the public.

Here, we provide two brief examples of visual communication that are of particular relevance to sustainability. One is a system of visuals used for solving 'wicked' problems (Text box 1: architectural drawing); the other is a digital platform for communicating landscape sustainability (Text box 2: biodiversity planning toolkit; Biodiversity Planning Toolkit 2016).

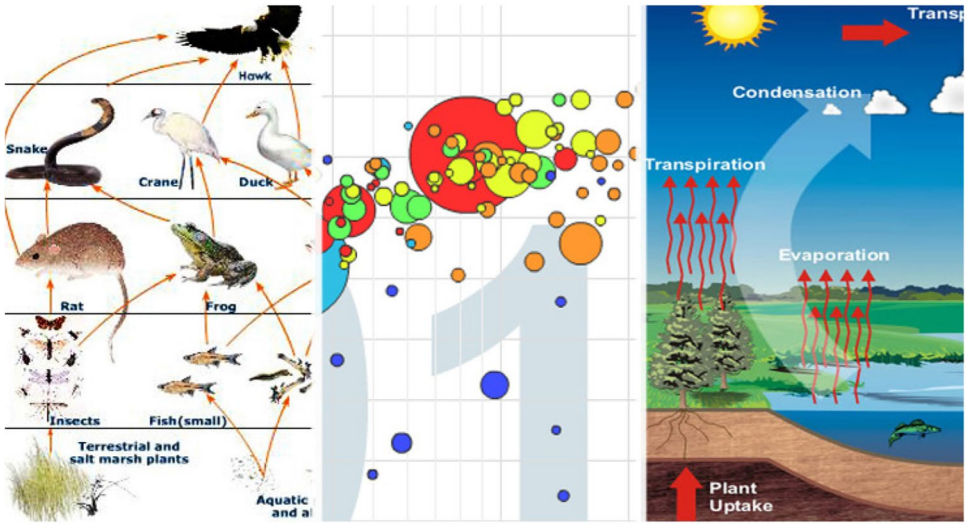

Fig. 3 Examples of visual communication for sustainability that transformed society: the Foodweb, Gapminder World and the Water cycle

Text box 1: Architectural Drawing

Architecture employs a suite of visual methods for solving wicked problems developed over millennia (Faste & Faste, 2012; Kennedy-Clark, 2013; Kolko, 2009). A single architectural plan can express overall building form, materials, construction details, the ambiance of spaces and the professionalism of the architect. The viewer can shift their mind across different ideas by directing their attention across the image. The architect's visual toolkit comprises several elements:

- Sketching helps designers to understand a problem and potential solutions in new ways. Strategies can be tested through multiple iterations with rapid feedback.
- Drawing conventions allow complex forms to be represented simply.
- Architectural drafting provides a holistic framework for coordinating the work of multiple disciplines.
- 3D computer models help to design and to express possible scenarios to non-experts.
- Building Information Modelling (BIM) enriches 3D models with a multitude of quantitative data.

No equivalent system has yet been developed for designing integrated solutions to wicked sustainability problems. Many of the needs for addressing sustainability problems are shared with architectural design, highlighting the applicability of visual design tools. However, the scale, stakeholders, and challenges vary greatly. Developing design tools for sustainability requires substantial further research, practical application and critique.

Text box 2: Biodiversity Planning Toolkit

The United Kingdom's Biodiversity Planning Toolkit uses an online interactive landscape to educate users about biodiversity and land developments (Biodiversity Planning Toolkit, 2016). It is highly visual and involves a number of strategies for generating interest, communicating complex ideas and facilitating holistic thinking on sustainability.

- An image of an idealised landscape is used to navigate content. It helps to express several layers of meaning while showing specific landscape strategies in a broader context.
- The familiar landscape reduces the conceptual challenge of highly abstract thinking. This makes the information accessible to a broader spectrum of society.
- The interactive interface allows users to direct their attention towards issues of personal interest.

Despite its successful execution of valuable strategies, significant limitations reduce the effectiveness of the Biodiversity Planning Toolkit. Site management has been discontinued and there is limited content available. Further, there are no opportunities for users to share ideas or contribute content.

When used effectively, visuals can express more complex ideas, more clearly, to a broader audience. They can also help us to solve complex problems, empower sustainability initiatives and influence values and behaviour. Our current visual and conceptual systems coevolved over centuries of cultural history, but they can also be strategically designed to provide new insights and shape the evolution of society. Digital environments provide an accessible platform for these developments. The technology and culture of the internet is rapidly shifting towards an emphasis on visuals. The five top visual-based websites alone (Instagram, Youtube, Reddit, Pinterest and Facebook) share 36 billion views per month (SimilarWeb 2016). The content from all these systems created and shared by users forms large global collaboration networks.

Tool 3: online collaboration networks

Online collaboration networks are digital tools that facilitate communication via the internet between communities with shared interests, and the interpersonal relationships that result. In recent years, there has been rapid exponential growth of online networks and user-generated content. This new paradigm of direct person to person communication is having significant global impacts on knowledge sharing,

Table 3 Potential qualities of online communication networks for sustainability

Quality	Common examples	Barriers it helps to address
Interdisciplinary	LinkedIn	Siloed institutions Uniform representation of world views Developing integrated solutions to wicked sustainability problems Ineffective thinking paradigms
Inclusive (crossing social/cultural, geographic barriers)	Gapminder (Gapminder 2016)	Uniform representation of world views Limited public engagement
Large scale and rapid growth	Facebook	Limited power of sustainability groups
User-generated content	Wikipedia	Limited power of sustainability groups Imbalance of forces that encourage unsustainable social values
Multi-way dialogue	Community discussion boards	Inadequate communication methods Limited public engagement
Rapid feedback cycle	Twitter	Inadequate communication methods
Engaging	Pinterest	Limited public engagement Ineffective strategy for directing social, economic and political influence
Decentralised control	Appropedia (Appropedia 2016), BitTorrent	Limited power of sustainability groups Imbalance of forces that encourage unsustainable social values

democracy, business and culture (Kelly 1998, Brockman 2011). Many of the characteristics of online networks have proven valuable for addressing many persistent barriers faced by the sustainability movement. They highlight its potential to "…capture imagination and interest and transform understanding, values and knowledge" (Blewitt 2009). In particular, these networks facilitate the sharing of knowledge, perspectives and collaboration across social barriers. They also provide tools for enhancing the social and political influence of sustainability groups. Some of these potential qualities are listed in Table 3 along with common examples and some of the barriers to sustainability they may help to address.

Networks can facilitate knowledge sharing and collaboration

By providing a platform for knowledge sharing and collaboration, online networks can help to address several barriers to sustainability. Free from geographic constraints, online networks can connect people from different organisations, disciplines and communities. If the interface allows, these communication channels can promote sharing of knowledge across silos. Real-time feedback loops can foster a more rapid evolution of ideas than annual conferences or quarterly publications. Dialogues between different cultural groups can help to critique and develop societal values. Inclusive, multi-way dialogues across disciplinary boundaries can go a long way towards integrating diverse knowledge and perspectives for more inclusive conceptual frameworks of sustainability.

When people and computers interact via networks, new intellectual pursuits become possible. By facilitating and structuring collaboration between people with different expertise, online networks can aid creative problem solving (Yu et al. 2012). For example, existing online networks assist in collective design (e.g., Linux), decision-making (e.g., Threadless), data analysis (e.g., citizen science) (Malone et al. 2010) and idea generation (e.g., Flood of Ideas 2011). The emerging field of Collective Intelligence develops strategies for generating positive outcomes from collective interactions in digital environments (Malone et al. 2010). Collective Intelligence also examines motivations for participation (Chamberlain et al. 2012), systems for expert collaboration (Hukkinen 2008), and group decision-making (Woolley et al. 2010). Again, these characteristics can help to advance sustainability, particularly in developing *integrated responses to 'wicked' sustainability problems*.

Fig. 4 Proposed applications of MetaMAP for strategic decision-making, research and education on sustainability. A 'landscape of ideas' guides users in developing conceptual systems models of sustainability issues, adding content and critiquing proposals

Networks can empower sustainability groups and initiatives

The large scale, social reach and independence of online networks can be applied to increase the influence of sustainability groups and initiatives. They can also empower citizens with increased access to knowledge and a stronger voice. The ubiquity of mobile devices allows even many remote communities most affected by sustainability challenges to participate in a global dialogue. Online networks can undergo rapid exponential growth with some becoming global comprising hundreds of millions of users. Networks of this scale provide opportunities for sustainability groups to influence public dialogue and political action in much the same way as traditional media. When run by online communities, networks with decentralised control can bypass established hierarchical institutions and social power structures. They can also empower sustainability experts and practitioners whose voices are often drowned out by powerful entities with media monopolies (Tegmark 2012). These networks can help sustainability advocates to form influential coalitions to enhance their real-world impact on society.

Each of these characteristics of *online communication networks* can help to address critical barriers to sustainability. However, positive outcomes are far from guaranteed. Many networks suffer from a lack of quality control and may reinforce rather than balance existing centres of power (Mergel 2011). To help advance sustainability, online networks must be carefully designed and managed.

We now provide a brief example of these principles in practice in the design of MetaMAP (Text box 3) (Fig. 4).

Text box 3: Example application of principles – MetaMAP

MetaMAP is a prototype visual platform for collaborating and sharing knowledge on sustainability. It was presented in Stockholm at the SDG Social Innovation Lab section of the International Conference on Sustainability Science 2017 (Maher, 2017) and described in detail elsewhere (Maher et al., 2018). It was designed based on insights gained from Synergy Map. MetaMAP helps users to understand sustainability challenges, develop solutions and share ideas, collaboratively. It is based on a new high-level conceptual framework of sustainability which is used to organise and navigate diverse content. This underlying framework is represented visually as a 'landscape of ideas'. Over this 'landscape', users add content and build up conceptual systems models of sustainability challenges. Users of MetaMAP undertake three primary activities (**Figure 4**):

1) organise and navigate content contributed by users forming a visual Atlas of Sustainability;

2) understand a specific sustainability challenge by synthesising multiple perspectives into a shared conceptual model (these models may be developed into new conceptual frameworks); and

3) examine scenarios and design interventions collaboratively.

Each of these *tools* identified in Synergy Map (**Figure 1**) are integrated into MetaMAP. Together they help to overcome a number of *barriers* to sustainability.

• The *integrated conceptual framework* upon which MetaMAP is based helps users to gain insight into sustainability challenges by seeing relationships among parts of the natural environment, built environment and society across multiple spatial and temporal scales. It provides a highly inclusive framework to help people from different backgrounds integrate diverse content and perspectives on sustainability issues into a common understanding.

• The *visual* interface acts as a common language across disciplines and helps to describe complex relationships among issues vividly. Manipulating these visuals helps users to apply design thinking to the design of sustainability initiatives.

• The *online community* associated with MetaMAP helps users to share knowledge, develop ideas collaboratively and provide input and critique on proposed sustainability initiatives.

Using Synergy Map to inform the design of MetaMAP helped to develop strong synergies among these digital and conceptual elements.

Discussion

Synergy among tools

There are many ways that conceptual and digital tools could be combined into digital artefacts for sustainability. Possibilities might include decision-making tools, knowledge sharing platforms, interactive data visualisation, even a 'Whole Earth Simulator' like the proposed FuturICT project (Helbing 2012). These tools are powerful in their own right, but when combined successfully, each tool enhances the effectiveness of the others. Understanding these synergies supports the design of effective digital artefacts for sustainability. Figure 5 describes some of the synergies among these tools, expanded here. *Integrated conceptual frameworks* provide a clear structure of ideas making *visual communication* effective. *Visual communication* in turn allows for a high density of information and expression of complex relationships and emergent properties. Most importantly, visuals can inspire a collective mental image of *integrated conceptual frameworks*. Integrated frameworks support *online communication networks* by providing a meaningful structure for knowledge sharing and discussion between disciplines. Frameworks such as social–ecological systems may help to connect people based on the relationships found in nature and society (Guerrero et al. 2015). *Online networks* can help practitioners and researchers to develop more integrated *frameworks* of sustainability collectively by connecting people from different backgrounds and with different experiences and world views. These platforms provide easily accessible avenues for rapid input and broad collaboration. Finally, *visuals* can enhance *online networks* by providing a common language and a focal point around which to gather. These tools will likely be the greatest benefit to sustainability when combined.

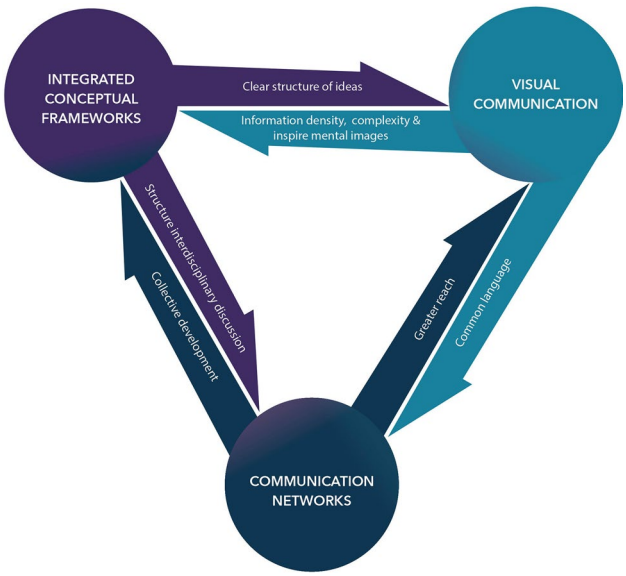

Fig. 5 Synergy between digital and conceptual tools. Each of the three tools (in circles) can enhance the effectiveness of each of the others. This is represented by the arrows. The text within describes some of the ways one enhances the other

The strong synergies between these conceptual and digital tools highlight their potential to address multiple barriers to sustainability simultaneously. This is expressed in Fig. 1 from right to left as: a *digital artefact* for sustainability founded on *integrated conceptual frameworks, visual communication* and *online collaboration networks* may help to address a range of *institutional, conceptual, communication* and *social power barriers*. This leverage makes them prime candidates for directing intellectual and financial resources.

Challenges to combining tools

There are undoubtedly a number of challenges to combining these three tools for sustainability. This combination requires collaboration across the disciplinary silos it is seeking to break. However, rapid growth in transdisciplinary research provides many strong precedents for breaking down these silos (Brandt et al. 2013; Cronin 2008; Harris et al. 2010; Lang et al. 2012). There are also many technical challenges involved with designing and building a digital platform which combines these new conceptual and digital systems. Creating interactive visuals is technically complex, requiring substantial resources.

Perhaps most significant is the conceptual challenge of integrating multiple conceptual frameworks into a cohesive whole. This requires a broad understanding of several sustainability disciplines, their perspectives and key concepts. Beyond their use in digital platforms, integrating conceptual frameworks of sustainability is critical to the field generally and research pursuing this should be prioritised (Miller 2013). Research through design methods is well-suited to this type of synthesis.

Conclusions

To aid in the design of digital collaboration tools for sustainability, we developed the Synergy Map. It establishes and maps relationships among key barriers to sustainability, identifies tools to help address them, synergy among these tools and highlights their potential for synthesis into digital artefacts. For each tool (*integrated conceptual frameworks, visual communication* and *online networks*) we introduced relevant theory, values to sustainability, some examples and some of the ways they help to address critical barriers. The tools can help to address several barriers to sustainability by

improving how we think, communicate and collaborate. The synergy among them provides a strong foundation for the design of digital artefacts to advance sustainability.

As products of culture, conceptual frameworks both express and influence our values. To shape a more sustainable world view of global society and bring about a paradigm shift towards sustainability they need to be expressed vividly in the public domain. Creating digital artefacts by combining new theoretical developments in Sustainability Science with recent advances in communication and networking technologies, offers substantial potential for advancing sustainability on multiple fronts. Used effectively, they can increase understanding, shape values and empower sustainability initiatives and the people who pursue them.

Further research

Further research into the development and use of these tools can help to improve the effectiveness of digital artefacts for advancing sustainability. Some core research agendas emerge: (1) understanding the needs and motives of different groups pursuing sustainability that might be addressed through digital artefacts; (2) understanding the potential of conceptual frameworks in the context of digital artefacts; and (3) developing more integrated conceptual frameworks as a foundation for interdisciplinary collaboration. Like most 'wicked' problems, many of these challenges will be best understood and addressed in the context of real projects.

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