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Understanding media multiplicities

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ABSTRACT

Internet of Things (IoT) technologies enable new forms of media artworks. 'Media multiplicities' are defined here as creative media experiences made up of multiples of interacting and coordinated devices. In this paper, we review the state of the art of multiplicitous media artworks and provide a systematic analysis of the novel affordances and different forms such artworks can take, specifically that they are spatial, scalable, scatterable and sensing. We consider the analysis of media multiplicities from the point of view of both user experience and creative production. We offer three primary axes through which a categorisation of multiplicitous media forms can be framed: substrate versus object; composed versus self-organised, and homogeneous versus heterogeneous. We also analyse how the number of elements in the multiplicities (from tens to tens of thousands and beyond) affects the qualities of the experience.

1. Introduction

In this paper, we discuss 'media multiplicities': distributed networks of physical entities that act collectively as media in a coordinated manner according to a person's creative intentions. We are seeing a proliferation of creative technology practices that make use of large networks of devices or elements, from individual LEDs forming media faćades, to multi-speaker systems, to swarms of drones. Such practices have been made increasingly viable and powerful by relentless increases in computing speed and network bandwidth, along with the emerging technologies of the internet of things (IoT) on the hardware side, and increasingly fluid creative programming methods and technologies on the software side.

This paper discusses the nature of this emerging world of media multiplicities in terms of creative, technical and experiential factors. It elaborates on ideas discussed in the summary article [1]. At its core is the question: does the emergence of media multiplicities constitute a radical departure from existing media forms, leading to novel forms of user experience? If so, what is the character that defines this distinction? Of particular importance, we will claim, the fluidity between substrates and objects is a defining feature of media multiplicities that marks a departure from existing media. Whilst this change may initially be considered as one that mainly concerns artworks and media, it also has significance for more general issues of user experience in pervasive computing, in which large networks of devices engage in coordinated action or sensing.

2. Background

We consider the following projects to be examples of media multiplicities. (i) The Spaxels Project[1] is a network of quadrotor drones each with a powerful RGB LED, allowing each drone to act as a moving point of light, or a 'spatial pixel'. (ii) Hiroshi Ishii's vision of 'radical atoms' [2], such as his dynamic tabletops, depict a world in which physical objects become creative media surfaces. (iii) Our own work in distributed Interactive Audio Devices (DIADs) [3,4], networks of portable Raspberry Pi powered speakers that can be controlled remotely, enable portable multi-speaker music, a phenomenon that has also been explored through various mobile phone and tablet orchestras. (iv) Media architecture, from the Blinkenlights project [5] to Squidsoup's volumetric LED spaces [6] (Fig. 1), provides coordinated illumination from multiple points on a room, building or city scale.

In each case, something that is itself a medium acts as part of something else that is also a medium. This is not in itself a new thing; screens are made of pixels, and home stereo systems consist of multiple speakers. The combining of media to create aggregate media leads to new properties in the new aggregate; multiple speakers afford spatial effects, pixel-screens afford the creation of an image from simple lights. But at the same time a new phase seems to be emerging. In (i) and (ii), the motility of the parts, and similarly in (iii) their portability, is one important feature that we see increasingly. With this comes a new ambiguity as to what the medium is, how it will be experienced, or what the conditions for the production of its 'content' are. Similar

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[1] https://www.spaxels.at/.

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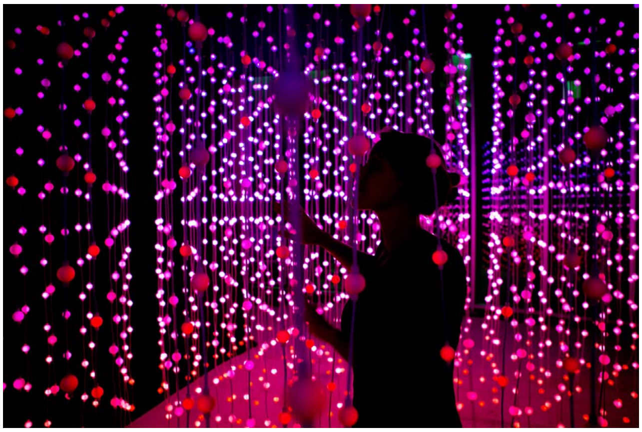

Fig. 1. Squidsoup's Ocean of Light installation is a 3-dimensional grid (voxel facade) of individually addressable LED lights, that can be used for presentation of pre-programmed content. Image Credit Paul Blakemore (Creative Commons CC BY-NC-ND 2.0).

ambiguities exist with screens and speakers, and have been teased out extensively by media artists; so there is no specific technology that has prompted a step change in how we experience media, rather a gradual evolution towards something that has novel properties. From the point of view of creating content, examples of (iv), media architecture, although not involving moving parts, involve creating highly site-specific coordinated lighting behaviours that also do not generally conform to the notion of the screen. The resulting media structures are sometimes just big screens, but in other more low-resolution scenarios, may not be able to have images played on them. More generally, even if image reproduction is possible, this may not be the primary or optimum way to make use of the medium. Related to these points, these projects reveal a degree of diversity and specificity, whereby novel, one-off media structures can easily be created for specific physical contexts, or with sculptural qualities that structure or form part of the medium.

2.1. Trends

There is no one technological change underlying the arrival of such media multiplicities, but several contributing developments. Most critical is the shrinking in size and also in price of powerful digital technologies, particularly CPUs and single board computers. Second is the increasing capacity, range, speed and sophistication of contemporary digital networks. Third are the technologies of portability: battery power and wireless communication. Fourth is the advancement of robust sensors and actuators. Fifth are advances in manufacturing, particularly rapid prototyping. Lastly, we have the ongoing improvement of computational intelligence.

2.2. Simultaneous convergence and divergence

At a higher level, one of the effects of such changes is the convergence of media forms around digital systems, following the trajectory towards increasingly ubiquitous or pervasive computing [7,8]. Media devices, even minuscule ones, increasingly share the common features of a computer: a processor, memory, storage, network and serial connectivity, and a familiar operating system that is host to reconfigurable software. Thus TVs, music players, lights, games consoles and mechatronics objects are increasingly exhibiting overlapping functionality, and media platforms increasingly facilitate interoperability between media types, as well as increasingly nested media types (e.g., you can have a video in a webpage but you can also have a hyperlink in a video).

Counteracting this convergence is a divergence in the form and sensor/actuator attributes of such digital devices, given that it is increasingly easy to build digital-physical systems for dedicated purposes (thus for example we are becoming multi-device users, with multiple dedicated devices such as laptops, phones, tablets, fitness trackers and headsets). Consequently, increasingly specific media contexts are mediated by increasingly generic software and hardware standards and specifications.

2.3. Key affordances

In addition to these contextual factors, feeding into the emerging world of media multiplicities, the bringing together of media devices in multiples leads to several new properties at the higher level, which we refer to as a set of four S's:

- **Spatial**: This first property has been mentioned above already. Multiplicities afford spatial distribution, as in distributed multi-speaker systems and immersive visual experiences. Headphones and VR headsets work to reproduce spatial effects at extremely close proximity, but increasingly we also see the embedding of media into large-scale contexts. The effect of spatially distributed media affords immersive experiences, in single and multi-user cases [9].
- **Scatterable**: We proposed 'scatterable' media to describe both spatiality and motility or portability: scatterable media can be moved around or can move themselves to be reconfigured spatially. This is increasingly easy with developments in portable wireless, battery powered devices and robotics.
- **Sensing**: Merrill et al. [10] describe sensor network user interfaces (SNUIs) as multiplicities of devices with coordinated sensors that form a single user interface. SNUIs are able to build complex distributed representations of their environment, and share this information. They can be readily employed for complex interactive data-display, as in interactive data sonification [11].
- **Scalable**: Network communication technologies have enabled massively scalable networks of devices. The media multiplicities described above have no fixed size; elements can be added to or removed from the multiplicity without any major reconfiguration (caveats to this are the issue of network scalability, and the context in which the multiplicity is being used, which may also impose requirements on the number and distribution of devices). Increasingly, technology affords multiplicitous media aggregates with no fixed size, and the scalability of specific multiplicitous media works will depend only the adaptivity of the work being composed.

2.4. Demands of content creation

Creating content for multiplicitous media requires platforms that allow rapid development appropriate to the creative environment, the main feature of which is that behaviour needs to be ported to multiple devices. This is well established in the world of networked music, with creative paradigms [12,13] and easy-to-use networking platforms [14,15] proliferating. Here, as in the discussions of authoring systems such as in digital music (e.g., [16,17]), we expect that well-designed constraints will be key to effective platforms. Creativity in media multiplicities additionally points to two major requirements of the creative technology:

- **Adaptation**: Media multiplicities operate in highly uncertain environments, and their design will be easier the more easily they can adapt to their environments. All of the above properties speak to this need. Spatially distributed, scatterable and scalable networks of devices are quite the opposite of the reliable consistency of the rectangular TV screen or stereo headphones. Multiplicities such as mobile phone orchestras might be made out of heterogeneous devices with different CPUs, sensors, speakers and so on. Authoring for such environments requires creating system behaviours that are suited to their context, and adaptive designs will be useful just as well-designed websites adapt to different device screens and

interfaces [18]. If elements move, or are added or removed, how does this affect the content? How do we build systems that cater for all situations or fail gracefully in limiting circumstances?
- **Simulation**: Not only are the circumstances unpredictable, but it may not even be practical to use any real configuration of the hardware in development. For example, developing behaviours for the Spaxels does not require firing up all of the drones, but instead modelling movement in a 3D application. Sophisticated simulation allows one to get a more detailed idea of what the acoustical and optical qualities are of the given context. For example, it is used by acoustic designers for modelling concert stage rigs prior to install. Whereas it is fine to work on content on a computer monitor that will be shown on a cinema screen, media multiplicities will increasingly require advanced simulation environments in which device properties can be modelled and behaviours simulated.

We will not devote any more discussion to the creation challenges for media multiplicities, which we discuss to some extent in other papers [4,19,20] and instead focus on user experience issues.

3. Characterising media multiplicities

In this section we consider several axes that provide a core characterisation underlying some of the key differences in forms of media multiplicities. These are (a) the specific numbers of elements involved, (b) whether the multiplicity is treated as a set of objects or as a substrate for media presentation, (c) the homogeneity and heterogeneity of the multiplicity, and (d) whether the system content is composed or self-organised.

3.1. Imagining media multiplicities in numbers

Beyond the leap from one to many, we could ask what is the threshold at which something is perceived as multiplicitous? Instead we prefer to look at different quantities in terms of characteristics that inform the design of media multiplicities (see Table 1), without any one numeric threshold being given priority. Drawing on numeric issues from a range of disciplines, we consider how multiplicities at different orders may be used to achieve different effects.

Ones and tens. How we interact with a quantity of entities depends on certain psychological constraints. Kaufman introduced the concept of 'subitizing' [21,22] to describe our ability to near-instantly judge the number of objects for quantities up to around four (the 'subitizing range'). Above the number four, we resort to counting proper. Thus it would be reasonable to suggest that the number four is the first real multiplicity threshold. Miller's famous 'magic number' 7 ± 2 [23], a widely cited rule for the number of elements that can be held in 'working memory', is another important cognitively grounded threshold. This threshold is specific to our awareness of the distinct content, locations or actions of elements, rather than to the countability of the elements. Equally, human group dynamics suggest other natural orders associated with 'manageability'; 10–12 is a typical range for sporting team sizes and has been identified as an ideal group size for decision-making, such as in juries in many countries [24,25]. Such orders correspond to perceptual properties of different sized musical groups and the effect of laying different voices on top of each other. Large ensembles can play in more or less coherent ways, creating the effect of a single entity or multiple competing voices. Small rock and jazz ensembles are able to fill the audio spectrum and create a complexity of interaction between a handful of voices.

Table 1
Some specific numbers and their significance to multiplicities.

Num	Quality
2	Technically multiple
4	Subitizing threshold
7 ± 2	Classic memory rule
12	Handful, manageable
20	Number of sounds accurately estimated
150	Dunbar's number: number of people in friendship network
3000	Number of bricks in a normal-sized living room
6240	Pixels in classic Nokia phone screen
10,000	Birds in a starling flock
150,000–200,000	Armies in contemporary movies such as Lord of the Rings and Troy
> 1,000,000,000	Pixels in largest video walls

Hundreds. Somewhere between 10 and 100 we transition to large numbers, where it is no longer conceivable to attend to each element in turn. For example Martens et al. [26] showed that estimation accuracy of the number of tic tacs in a box, perceived acoustically when shaken, plateaus over 20. 100 could be considered a lower limit for the size of a crowd, and a theory developed by evolutionary psychologist Robin Dunbar [27] predicts the natural cognitive limit for human social relations to be around 150. Spaxel shows have been presented in the 100s, and large buildings used in media facades often have 100s of windows that can be used as low-resolution pixels, as in the Blinkenlights project [5].

Thousands. Around 1000 we start to see the possibility for elements to form rich substrates for the production of figures, where typically the component objects are completely subsumed by the image. Minimal effective screen resolution comes in at well under 10,000 pixels. At 96×65, Nokia's 1101 cellphone, the most popular cellphone ever, has only 6240 pixels. Although definitively from the pre-smartphone era, the screen is sufficient to display several lines of text, simple images, and has been a platform for successful games.

For the sake of comparison in the audio realm, one can think of audio resolution in terms of the spectral decomposition of sounds (as an alternative to the sample rate of an audio waveform). According to basic audio theory, a sound can be described as the superposition of a weighted series of pure sine waves. Thus you can use a process of *additive synthesis* to recreate sounds from basic oscillator elements. The quality of reproduction depends on the nature of the sound you want to reproduce. Tones are easier to reproduce than noises. 100s of oscillators will easily reproduce many sounds. 1000s of oscillators will achieve a very high definition of reproduction.

Tens and hundreds of thousands. Likewise, mobile agents also begin to form rich figures in the thousands. We witness spectacular emergent effects when birds, fish and insects gather in large numbers. Starling flocks that can reach sizes of up to 10,000 exhibit a well-documented form of self-organised behaviour in which the flock moves with the appearance of a single animated object.

As computer graphics special effects are increasingly used in big-budget movies the sizes of fictional armies has grown until they stretch to the horizon. In The Lord of the Rings 200,000 characters might fit into a single frame. In Troy, the real historical numbers were doubled to make a better impression. In these cases, the multiplicity forms a wash of activity which we tend to perceive globally. But we can also continue focus on the detail of individual elements.

Millions, billions and astronomical numbers. The world's highest resolution video wall at the time of writing is at Dubai Mall,[2] with a resolution of 1,700,352,000 pixels, covering an area 14 m × 50 m. But since video wall technology has been scalable for many years now, there is no upper limit to the potential size of such a screen.

The media futures imagined by Hiroshii Ishii consist of 'radical atoms' [2], tiny mechatronic components that form interactive surfaces and collective behaviours. Research in nanotech and micro-scale robotics is contributing to a world where such interactive systems are beginning to seem feasible. But based on existing trends we might

[2] http://www.sixteen-nine.net/2017/08/02/amazing-dubai-mall-turns-on-worlds-largest-oled-video-wall/.

Fig. 2. For a substrate, the individual objects act together to present media content, while for a group of objects the significance of the object itself is primary.

reasonably expect advanced media multiplicities, as defined above, with component numbers in the millions and billions, that take on the properties of materials, composed of media atoms.

3.2. Substrates versus objects

A core axis along which we can compare media multiplicities, and perhaps the distinction that most clearly defines their novel nature, is the extent to which the system acts as a substrate for *content*, or instead is perceived as a series of standalone objects (Fig. 2).

Similar to the Spaxels, the Pixelbots project [28] consists of a series of motile pixel-like elements, this time limited to movement on a 2D surface. As they presently stand, small in number though they may be, the Pixelbots and Spaxels offer a taste of a future in which massive swarms of drones might create impromptu screens on surfaces or in the sky: dense, solid, flat or undulating surfaces comprised of colour pixels that act as a substrate for the production of an image. At the moment your awareness is drawn to the image being produced, you lose sense of the objects making up the substrate. Pixels on a screen of course exhibit this property. Rather than being objects themselves, as far as your experience is concerned, they disappear into the substrate they form, which becomes a conduit for the portrayal of other virtual objects.

Specifically, we see "substrate" here as referring to the complex of technologies and materials required to create *images* (sonic, visual, etc.). Technically the screen is accompanied by other elements required for the production of the image, such as the computer technology that is driving the screen. A Pixelbot or Spaxel screen, like any digitally produced image, would still comprise a series of distinct and independent objects, the agents themselves, and there is the capacity to redirect focus onto one or more of these objects alone, rather than the substrate they form. The agents may scatter, forcing you to look at only one at a time, or they may behave in uncoordinated ways that break the holistic effect, completely but temporarily erasing the multiplicitous nature of the system itself. This depends on the scale at which they exist, informed by our discussion of numbers above.

The substrate/object relationship is different in the domain of sound. A loudspeaker is a single object that acts as a substrate for sonic images, so the speaker can seemingly be at once object and substrate. We can be more or less focused on the object or on the content being rendered through that object. An appeal to the accuracy of reproduction of a high-fidelity sound system may imply the making-invisible of the speaker as an object of focus, and spatial sound reproduction may decouple the physical location of speakers from the perception of sound sources to an extent, but speakers are nevertheless objects of conscious attention in many listening situations. For example, a subwoofer playing electronically-produced sine tones need not be considered a conduit of images, but simply a sound-making object in the world. Note however that as far as *spatial* sonic imagery goes, the multiplicity is key to the creation of the substrate.

Some media multiplicities, particularly those which allow autonomous movement of the elements, exhibit the capacity for control over the relative emphasis of perspectives between objects and substrates. Although not the only way to achieve this, the ability for the elements to move freely is one way to achieve this free movement along this axis.

A common, although not essential, assumption is that in the formation of the substrate the elements will be regularly arranged and homogenous. By contrast, when a multiplicity is disordered there is no pre-existing relationship between a particular pixel and its location, meaning that it harder, but by no means impossible, for it to be used as a substrate for the presentation of images or other spatially ordered media.

3.3. Heterogeneity versus homogeneity

An even more basic property of a multiplicity is the homogeneity or heterogeneity of the parts that comprise it (Fig. 3). Homogeneity and heterogeneity may occur at different levels; people assume different roles in a society (heterogeneity) despite the commonalities of their bodies and brains (homogeneity). Likewise, the same role can be performed by very different people. A question for any system then is in what way the elements are interchangeable; are the core elements homogenous or heterogeneous, and are their outputs homogeneous or heterogeneous? Pixels may be physically identical, thus interchangeable, but once they are assigned locations on a grid we take into

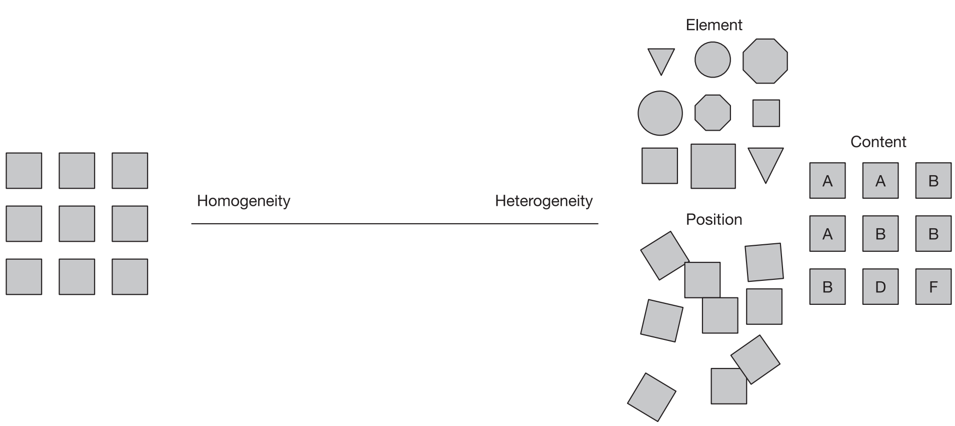

Fig. 3. Homogeneity and Heterogeneity – heterogeneity can occur in several main ways.

account those positions as distinct properties of the pixels if we want to use the multiplicity to produce a coherent image. Pixels are homogeneous elements taking heterogeneous forms dependent on their location.

A more elementary form of multiplicity is one in which the elements are identical and they also perform the same identical role, exhibiting the same behaviour. We might describe this as a *forest*, many instances of the same thing creating a homogenous multiplicity. Many current light artworks, lacking networks of communication, complex sensors or positioning, take this form. Zimoun's sound sculptures also take this form.

Next consider a set of elements that is still essentially homogenous but that can be systematically varied, but without resulting in a structured image. We can describe these as *spectra*. It is common for artists to work systematically through variations on a narrow theme, such as in the well-known series of Mondrian and Rothko. We also see this in contemporary parametric design, which formalises the process by which a design can be systematically varied. In media multiplicities, spectra might take the form of homogeneous elements exhibiting variations, such as a multi-speaker artwork where each speaker projects a voice talking.

At the other extreme is the situation in which the elements are heterogeneous and it becomes less meaningful to treat them as variations of the same thing. Computer generated armies are a typical example, comprising, for example, foot soldiers, cavalry, flying dragons and catapults. Within each of the categories, there may be forests or spectra, as described above: variations of the same sort of thing. But between heterogeneous types there is no strict commonality. This is familiar in music; an orchestra combining different groupings of elements, within which there is further variation; brass sounds includes tuba sounds and trumpet sounds, and so on.

3.4. Composed versus self-organised

A final property that is important in our discussion of multiplicities, is whether the multiplicity is organised by a central plan or composition, or whether the parts of the multiplicity organise themselves and primarily behave based on a set of localised and decentralised processes and interactions (Fig. 4). This distinction is often described in terms of top-down and bottom-up systems of organisation.

A designed ecosystem, where different elements interact and influence each other without any top-down or external control, invites a range of possible behaviours based on the principle of self-organisation. A classic example of this is the flocking algorithm, widely used in generative artworks. Alternatively, a *composition* is where the designed structure of the whole is more significant than the parts, so that the parts become subsumed as distinct entities, instead only serving the whole. This is most commonly typified by the substrates discussed earlier – screens or displays made up of pixels the only purpose of which is to render images. However, even with regular screens there are exceptions, for example in the case of GPU-based cellular automata and reaction diffusion models, where the GPU architecture is not only delivering image-rendering services but actually calculating the progression of a bottom-up system.

Pixels, while being directly adjacent to their neighbour pixels, know nothing of their neighbour's state and only change their own state based on instructions resident in the transmitted composition. They exist in a multiplicity as a hub-and-spokes structure, rather than a mesh. By contrast some systems may have no access to a common central controller and rely on local interactions. This affects the system's ability to enact composed behaviours, but since computers can simulate self-organised processes, all systems can exhibit these.

In contrast, a self-organised system will make use of communication between elements within the multiplicity, with each one altering its own behaviour or characteristics based on the state of its neighbours (or sometimes other stimuli), following given rules. There are many systems of this nature, and in most cases where these are used the way in which the self-organisation results in patterns or behaviours is the central substance of the multiplicity.

4. Inclusive and extended definitions of media multiplicities

The examples used in this discussion of the characteristics of media multiplicities range from regular screens and speakers to advanced networked mobile systems. Which of these should actually be defined as media multiplicities as opposed to traditional digital media technologies? Should a quadraphonic sound system count, for example?

We propose that media multiplicities can be an inclusive term; the obvious prerequisites are the basic characteristics of digital media, that the device is capable of acting as medium for information, combined with the existence of multiples. But the substrate-object dimension offers a particularly important characterisation of contemporary trends in media multiplicities, and an extended class of media multiplicities exhibit freedom of movement along each of the dimensions listed: between substrate and object, between heterogeneous and homogeneous states, and between composed and self-organised modes.

Significant innovations in media multiplicities would then be characterised by the enabling of more radical flexibility along these axes. Advanced media multiplicities would allow all of their components to move and rearrange, enabling the shift between a media substrate and a set of media objects. They would be able to adapt in form so as to achieve heterogeneous form from homogeneous origins. And in their movement and restructuring, they would behave in adaptive and self-organised ways, whilst still enabling creators to design content in a top-down manner.

A possible source of confusion in defining media multiplicities lies in whether we accept virtual media multiplicities existing in virtual world models. Imagine wearing a VR headset and looking at a single, virtual TV screen within the virtual space. Now imagine thousands of virtual TV screens, flying around to form new configurations. This is exactly the kind of thing we imagine typifying advanced media multiplicities. Being virtual, the screens could morph into other forms, subdivide, combine and so on. But by admitting such virtual multiplicities we also seem to trivialise the definition. In virtual worlds we are unencumbered by positioning, morphology, network communication, movement and so on. It is more trivial to create what we have described as media multiplicities, although of course we are still constrained by concepts of object boundedness and individuality that are arguably

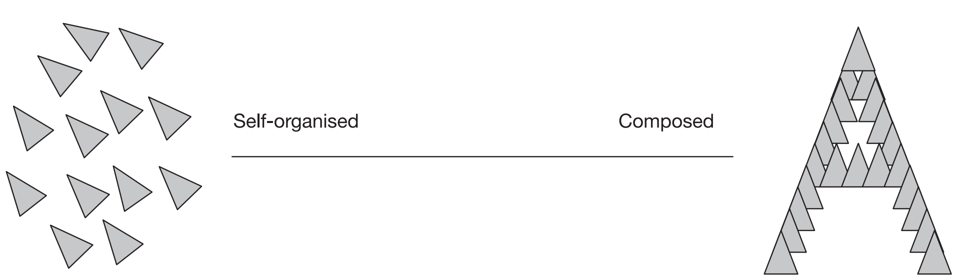

Fig. 4. A set of self-organised elements can form flocks and other emergent patterns, while a top-down composed process can create specific structures.

more prominent in programming languages than they are in the real world. But our definition of media multiplicities refers strictly to multiplicities of physical devices.

5. Discussion of examples

In this section, examples of media multiplicities will be discussed, some mentioned already, and the proposed descriptor categories will be applied to each of them so that the framework can be illustrated.

Dialtones, a 2001 work by Golan Levin and collaborators [29], is an early example of the use of the mobile phones of the audience as a media multiplicity. In this work, custom mobile phone ringtones were installed on audience members' mobile phones based on their seat position in a theatre, and then groups of these phones were called by the performer simultaneously, using specialised software and hardware. This work, although early, demonstrates the characteristics we have been describing in this paper quite clearly. This was a composed work, with both the spatial distribution of the devices and the sounds carefully controlled by the performer. This did involve some heterogeneity of devices, to the extent that the mobile phones were not all of the same model and construction, but conversely given the careful specification of particular ringtones, there was also quite a great deal of homogeneity in the control over the sound. The work was able to play with the role of the multiplicity as a substrate versus a series of distinct objects, by playing with the degree of coordination of the ringtones. Given that the technology of the time offered only coarse-grained temporal synchronisation and positioning, the potential for the multiplicity to create coordinated images was limited. The strategy shows that technology limitations were quite significant, to the extent that practical work-arounds (using seat number information to allocate ringtones) were necessary for this work to be realised (see Fig. 5).

Spaxels [30] are quadrotors, each outfitted with a powerful RGB LED, that perform choreographed arial performances. While they do purport to create a substrate system, able to form shapes and images while hovering in a group, they are possibly better understood as co-ordinated objects which form a type of group performance. As a medium or substrate for the transmission of other complex media, their utility is currently limited. But theoretically there is no reason why this substrate capability could not be enhanced in future iterations; as quadrotors drop in size and increase in capabilities it seems possible to achieve densities where the eye would resolve them as pixels (consider that current spaxels performances are just an order of magnitude below the Nokia 1101 screen resolution). A spaxel system also demonstrates the possibility for adaptive pixel density – areas of high detail could be served by a higher number of spaxels while areas of little detail could be served by comparatively fewer. In terms of the two other description axes - the spaxels are homogenous, as each quadrotor is identical, and their actions are likely to be controlled from a central system, rather than self-organised in response to group characteristics (although its not difficult to imagine this being undertaken).

Fig. 5. *Dialtones* (*A telesymphony*), a 2001 performance by Golan Levin, used custom ringtones installed on the mobile phones of audience members seated in known positions within the performance space, and which were then rung systematically by the performer on stage. Image Copyright Ars Electronica (Creative Commons BY-NC-ND 2.0).

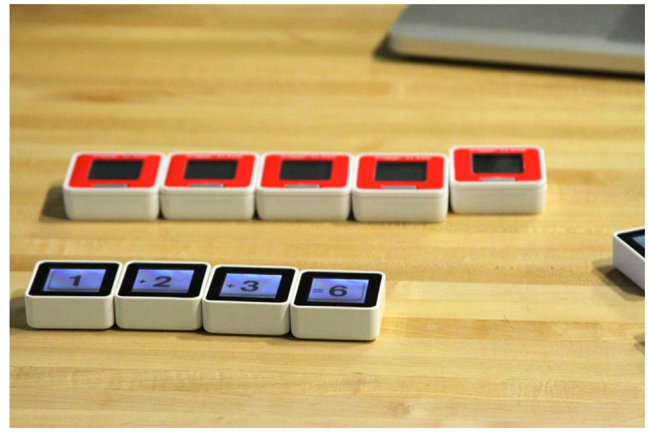

Fig. 6. Siftables are a set of small reconfigurable battery-powered devices which contain both a display and computing capabilities, and which exploit tangible interaction methods. Image Copyright J. Nathan Matias (Attribution-ShareAlike CC BY-SA 2.0).

A related system, a set of quadrotors with centrally controlled behaviour and onboard lighting, is the *Sparked* work of Cirque du Soleil.[3] Despite sophisticated and precise computer control that enables precise co-ordination, the focus is not on using the elements as a substrate, but on the individuality of each of the elements of the group, as the quadrotors are 'costumed' as magical decorative lampshades. Each lampshade has separate behaviours, but at times will dance co-operatively with the group. Here the work is focused on the individual objects.

The *DIADs* [3,4], developed by the authors, is another multiplicitous system that consists of a homogenous set of devices which form a substrate for audio media. They allow for compositions of either synthesized or sampled sound, to be played through the devices, as well as programs to be loaded so that each device can act as a self-organising unit. They are conceived of, and currently implemented as, homogenous device groups made up of 20 cm diameter spheres, but a range of designs and form factors are being developed.

Siftables [10] (Fig. 6) are a set of small reconfigurable battery-powered devices which contain both a display and computing capabilities, and are shaped like large Scrabble pieces.[4] They can be used to develop applications that employ tactile physical manipulation to engage users in tasks – especially relating to board games such as Scrabble or dominos. In the context of the framework discussed, this would be described as a largely self-organised system, with individual homogeneous objects. However, given enough of these devices it is easy to see how they could be positioned so as to become a substrate for rendering images. Similarly, the networking capabilities of these devices mean that the media designed for the system could be composed in a top-down manner – that the system's reaction to interaction could be centralised, with the output devoted entirely to centrally managed content. Given that the Siftables afford all of these possible design configurations, they can be considered advanced media multiplicities.

Ocean of Light, by Squidsoup (Fig. 1), is a volumetric display system that uses a 3-dimensional grid system of thousands of individually addressable LED lights, suspended in strings from a frame, usually above a stage or installation space. This system is nearly perfectly homogenous and can form a substrate for other media images and effects; custom

[3] https://www.youtube.com/watch?v=6C8OJsHfmpI.

[4] http://alumni.media.mit.edu/~dmerrill/siftables.html.

Table 2
Examples of artworks and other phenomena (both interactive and non-interactive; physical, physical/digital and digital) and their relationship to the description axes. This is by no means an exhaustive list. Notes: where works are marked 'substrate/object' there is a overall image, but the things making up the image are of interest, many of the works can be seen to use this connection to creative effect; 'self-organised' here includes systems where the elements merely act independently, without necessarily interacting; where relevant heterogeneous/homogenous refers to the physical elements making up the work, but can also refer to 'virtual' elements (as in Leber and Chesworth, or MIT's generative logo).

Work	Creator	Year	Description	Quantity	Substrate/Object	Composed/Self-Organised	Heterogeneous/ Homogeneous Components
186 prepared dc-motors, cotton balls, cardboard boxes 60 × 60 × 60 cm	Zimoun	2013	Multiplicity of the same basic pattern of movement of a cotton ball knocking against a cardboard box. Boxes are arranged in a tall turret that one can enter. The multiplicitous effect of the sound is spectrally and spatially rich	100s	Multiplicitous Objects	Self-Organised	Largely Homogenous
Spaxels: The Ars Electronica Quadcopter System	Ars Electronica Future Lab	2014	Swarm of quadcopters that can be used as "Spatial Pixels" or choreographed drones	10s	Low-fidelity Substrate	Composed	Homogenous
Distributed Interactive Audio Devices	Bown et al.	2013	System for creating and controlling populations of networked audio devices	10s	Substrate	Composed or Self-organised	Homogenous
Field	Anthony Gormley	1989	Multiplicity of clay figures handmade by children, filling a space	100,000s	Objects	Self-organised	Heterogenous
Mobile Phone Orchestra	Andrew Bluff	2013	Composition for live performance over users' iPhones. Program plays at synchronised times. Uses users' music libraries as source material	10s	Substrate	Self-organised	Heterogenous (different models of phone)
Autopoeisis	Ken Rinaldo	2000	15 robot sound sculptures that modify their behaviour based on the environment and each other	10s	Objects	Self-organised	Homogenous
Dialtones (A Telesymphony)	Levin et al.	2001	Early mobile phone "orchestra". Audience register phone numbers. Ringtones and seating positions are given to them. Performers trigger phones	10–100s	Substrate	Composed within variations	Heterogenous (different models of phone)
Siftables	Merrill et al.	2008	Hardware and software platform consisting of multiple square domino-like devices with screens. Respond digitally to tangible input	10s	Object-like but with two levels of substrate	Self-organised	Homogenous form, Heterogenous content
Ocean of Light	SquidSoup	2010	System for installing cubic volumes of LEDs in spaces	1000s	Substrate	Composed	Homogenous
Lord of the Rings armies (example of CGI massive multiplicities)	Massive Software	2001	System for programming the appearance and behaviour massive numbers of CGI characters for movies, includingAI behaviours	100,000s	Objects	Self-organised (with careful adjustment)	Heterogenous
Mexican Wave	Origin Unknown	–	The wave effect achieved by stadium crowd members performing a coordinated standing action	10,000s	Substrate	Self-organised	Homogenous
Radical Atoms	Hiroshi Ishii	2000s	Ishii's concept of the integration of digitally mediated control into physical media such as tabletops, via multiplicitous actuators	100–1000s	Substrate	Composed/ Programmed	Homogenous
Sparked	Cirque du Soleil	2014	A choreographed performance using quadcopters which allow everyday furniture (lampshades) to enter into a coordinated dance	8	Objects	Composed	Homogenous
Commonwealth Games Handover	Digital Pulse	2014	A choreographed dance piece where dancers constantly rearrange TV screens to form a larger image	18	Objects/Substrates	Composed	Heteorgenous (different sized screens)
WCMC Discovery Wall	Squint/Opera	2013	A large video wall, the elements of which are individual screens set behind lenses	2800	Substrate, at 2 levels	Composed	Homogenous (structured two-level system)
MIT Media Lab, Generative Logo	Richard	2011	A simple generative logo. A distinct version of the logo is produced for repeated personalised use by each member of the Media Lab	Astronomical	Objects	Self-organised	Heterogenous
Fake Fish Distribution	Bown and Britton	2012	A record produced as a 'limited edition digital download' in which 1000 variations of the musical content were produced systematically	1000	Objects	Composed	Heterogenous
This Is Before We Disappear From View	Sonia Leber and David Chesworth	2014	Fixed media sound work. Many voices rising in tone in the style of Shepard tones	10s	Substrate	Composed	Heterogenous
Knock On The Sky Listen To The Sound	Tiffany Singh	2011	Multiplicity of bamboo wind chimes arranged in a regular grid just above head height	10s–100s	Objects	Self-organised	Homogenous
Pulse Room	Rafael Lozano-Hemmer	2006	Hundreds of light bulbs arranged in a darkened room. Pulse measuring station detects pulse of participant making nearest light bulb flash. Pulses are pushed along the grid one by one, acting as a record of the recent audience's heartbeat	100s	Substrate/Object	Self-organised	Homogenous

(continued on next page)

Table 2 (*continued*)

Work	Creator	Year	Description	Quantity	Substrate/Object	Composed/Self-Organised	Heterogeneous/Homogeneous Components
Ping Genius Loci	Aether Architecture	2006	300 networked 'intelligent analogue pixels', physical forms that show either red, green or blue in a particular direction, are placed in a 20 m by 20 m grid	300	Substrate	Composed	Homogenous
Missing	Kyle McDonald, Aramique Krauthamer and Matt Mets	2012	50 robotic loudspeakers suspended from the ceiling turn to follow the installation participant as they move through the space	10s	Substrate	Self-organised	Homogenous
Definitions	Bryan Ma	2015	15 digital LCD displays show single words that are linked in sequence by their computed characteristics in MIT's ConceptNet semantic network	10s	Substrate	Self-organised	Homogenous
F21Thread	Breakfast	2015	Display built from 6400 electromechanical spools of thread capable of displaying colours. Used to display instagram photos	1000s	Substrate/Object	Composed	Homogenous
Ninety Six	Nils Vlker	2014	96 plastic bags with fans to inflate them are positioned on a wall in a grid, allowing them to act as a very low resolution display	100s	Substrate/Object	Composed	Homogenous
Bits And Pieces	Nils Vlker	2016	108 suspended expanding plastic framed Hoberman spheres are controlled by electromechanical system to produce wave-like patterns throughout a space	100s	Substrate/Object	Composed	Homogenous

software allows for the colour and brightness of each light to be controlled, and 3D animated forms can be rendered in the space. But as a low-resolution media environment that can be entered into, it does not always appear to participants as a screen. When an audience member is in the space, their relative proximity to individual lights breaks the effect of the environment as a renderer of images. The system's static and homogenous nature misses out on some of the aspects of advanced media multiplicities, but its scale, and the capacity for it to be entered into, create distinct user-experience effects. Squidsoup's new system *Bloom* reconceptualises *Ocean of Light* as a set of portable wifi-enabled Arduino devices [20,19].

In Table 2 we select a wide range of artworks and systems, from fully interactive, motile and hybrid physical-digital systems, to examples of static artworks, human group behaviours and so on, described using our axes.

6. Summary

This paper proposes the term 'media multiplicities' to capture a range of existing projects in multi-device media experiences, with a detailed categorisation and discussion of future directions. We characterise media multiplicities by examining three main characteristics: media multiplicity systems take elements of both a composite *substrate* and groups of individual *objects*; they are built of sometimes *homogenous* or *heterogenous* elements, spatial configurations and content, and their ability to move between heterogeneous and homogeneous content and structure can be more or less advanced. Their behaviour is sometimes centrally *composed* or directed, and in other cases defined by local *self-organising* process and interactions. Finally, the number of elements in the group helps to frame an understanding of the way in which the elements of the group are perceived, as individual elements and as a composite element.

The component properties of media multiplicities are themselves not really anything new, it is only the new speed, dexterity and precision with which we can develop these networks of devices that is rapidly changing. We believe there is a need to distinguish these defining properties and affordances, which suggest radical developments in the design of media experiences as they come together and increase in sophistication. We hope this allows a clearer charting of trends in the field – it can be seen that earlier media multiplicities were more likely to be made up of small sets of objects rather than forming substrates, to use fixed composed works and sets of homogenous devices, often with homogenous content. As technological capacity increases, there are more ways in which systems can situate themselves along these dimensions; multiplicities can now easily incorporate elements with self-organising capabilities, can incorporate heterogeneity amongst devices, and can smoothly shift between sets of objects and substrates.

As these capabilities become more widespread, the development of creative production techniques will be of particular interest for this field, for which we believe the creative power of *adaptation* and *simulation* will be essential. Designing for the vast possibilities that exist within the space defined by our axes will make production tools complex to build and understand. In the advanced case, this means systems in which the components can move of their own accord and hence restructure themselves collectively.

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