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Author:
Bown, O; Ferguson, S

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Abstract

Internet of Things (IoT) technologies enable new forms of media artworks. We are seeing the rise of 'media multiplicities', 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 homogeneity versus heterogeneity. We also how the number of elements in the multiplicities (from tens to tens of thousands and beyond) affects the form of the experience.

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Understanding Media Multiplicities (PREPRINT)

Oliver Bown and Sam Ferguson

1 Introduction

In this paper, we discuss "media multiplicities": distributed networks of physical or virtual 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 emerging technologies of the internet of things (IoT) on the hardware side, and advanced 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. At its core is the question: does the emergence of media multiplicities constitute a radical departure from existing media forms? If so, what is the character that defines this distinction? We identify three trends that have an important bearing on this question: the diversification of media contexts; the emerging fluidity between substrates and objects; and an increasing capacity for heterogeneity. In particular we see the fluidity between substrates and objects as 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 in pervasive computing, due to the fact that artworks offer an experimental platform to explore possibilities that ultimately lead to widely adopted capabilities.

2 Background

The following projects are all examples of media multiplicities. (i) The Spaxels Project is a network of quadrotor drones each with an RGB LED, allowing each drone to act as a moving point of light, or a 'spatial pixel'. (ii) Hiroshi Ishii's

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vision of ‘radical atoms’ [10], such as his dynamic tabletops, depict a world in which physical objects become creative media surfaces. (iii) Distributed Interactive Audio Devices (DIADs) [4, 3], networks of portable Raspberry Pi powered speakers that can be controlled remotely, enable portable multi-speaker music, as has also been displayed in the creation of ‘mobile phone orchestras’. (iv) Media architecture, from the Blinkenlights project to Squidsoup’s volumetric LED spaces [23] (Figure 1), provides coordinated illumination on a building or city scale.

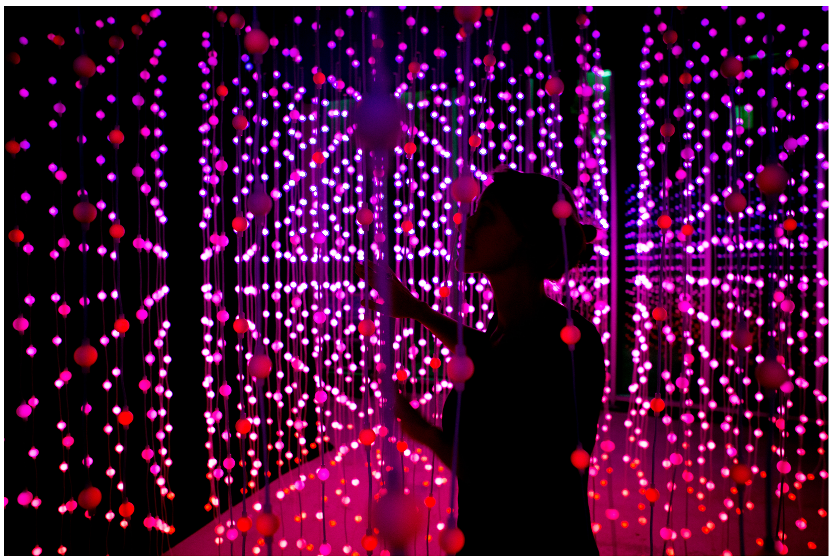

Figure 1: Squidsoup’s Ocean of Light installation is a 3-dimensional grid (voxel facade) of individually addressable LED lights, that can be used for presentation of pre-programmed content. Image Credit Paul Blakemore, (Creative Commons CC BY-NC-ND 2.0)

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 merging 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), (ii) and (iii), the motility of the parts, whether autonomous – as in (i) and (ii) – or acted upon – as in (iii) – is one particularly novel feature. 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 ambiguities exist with screens and speakers, and have been teased out extensively by media artists, so whether this is a step change or a gradual evolution may not be easy to answer, but the creative ambiguity is certainly more extreme. From the point of view of creating content, example (iv), although not involving moving parts, involves creating highly site-specific coordinated lighting behaviours that also do not generally conform to the notion of the screen. The resulting media structure may not be able to have images played on it, as such. More generally, even if image reproduction is possible, this may not be the primary or optimum way to experience it. Related to these points, these projects reveal a new 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

Thus whilst there seems to be a change taking place in the arrival of such media multiplicities, it is not clear exactly what distinguishes them from previous media. We can begin at least by being clear about some of the underlying trends relevant to this technology, and consider the affordances they offer. Most critical, of course, is the shrinking in size and also in price of powerful digital technologies. 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 we have 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 [17]. Media devices, even minuscule ones, increasingly share the common features of a computer: a processor, memory, storage, network and serial connectivity, and above all a familiar operating system that is host to endless existing software. Thus TVs, music players, lights, games consoles and mechatronics objects are increasingly exhibiting overlapping functions 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 actual manifestations of such digital devices, owing to the fact that it is increasingly easy to build digital-physical systems to one's specific needs. Thus increasingly specific media contexts are mediated themselves 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. Multiple speakers and multiple pixels can produce spatial effects in a variety of ways, but tend to easily afford more immersive experiences, especially in multi-user cases [21]. Spatial effects can be produced at extremely close proximity at one extreme, as in headphones and VR headsets, or can be embedded in environments, as in media facades.

- **Scatterable**: Much less familiar is the idea of 'scatterable' media, which involves both spatiality and motility (active or passive): scatterable media can be rapidly reconfigured spatially, without interrupting the media experience, and possibly even enhancing it.

- **Sensing**: Multiple sensing devices working together to provide an interface have been described as sensor network user interfaces [18]. They are able to build complex distributed representations of their environment, and share this information. They can be readily employed for complex data-display, as in data sonification [2].

- **Scalable**: Although there are TV screens of many different sizes, created out of the same basic pixels, TV screens are not readily scalable. But we can build TV walls, tiled from individual screens. Increasingly, multiplicitous media aggregates will have no fixed size and may dynamically scale depending on available resources or need.

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, 27] and easy-to-use networking platforms [20, 14] proliferating. Here, as is widely understood in the creation of new authoring technologies, as in the discussions of Magnusson, [15, 16], we expect that well-designed constraints will be key to effective platforms. Media multiplicities creativity additionally points to two major requirements of the creative technology:

- **Adaptation**: Media multiplicities operate in highly uncertain environments, and must 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 intelligently adapt to their context, just as well-designed websites adapt to different device screens and interfaces [1]. 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.

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, what is the threshold at which something is perceived as multiplicitous, and what are the different degrees of multiplicitousness?

Ones and Tens One answer comes in how we count. Following a number of studies, Kaufman introduced the concept of 'subitizing' [11, 6] 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' *seven* $+/-2$ [19], a widely cited rule for the number of elements that can be held in 'working memory', points to a similar 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. Around 10-12 might mark another threshold of manageability, although this is less tangibly supported by evidence. These are still easily imaginable quantities.

Social dynamics may also dictate how we relate to certain groupings. 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 many juries [24, 25]. Seven is also considered a good group size for decision-making [22]. Factors include the number of different views expressed, the complexity of managing the group, and the freedom people feel they have to contribute (larger groups, it is argued, become dominated by a *smaller* number of more confident individuals, whereas in smaller groups there is more equal participation).

We might also consider the auditory perception of these various quantities in terms of the sizes of bands, and thus the number of potentially perceptually distinguishable 'voices'. Rock and jazz groups of 3-4 members are common, 7-12 gets into big-band territory, and larger groupings such as choirs or full orchestras tend to increase the number of individuals involved in performing any particular voice.

In terms of the groupings of aesthetic objects, music provides some other interesting numerical foundations. There are twelve tones in the Western equal-tempered system. This system is derived from a more elementary pure temperament system based on Pythagorean principles of small harmonic ratios. The 1:2 ratio of the octave is recognised as the principle harmonic relationship universally across all cultures [26]. Second to this, and near universal, is the 2:3 ratio, known in the equal-tempered system as the 'fifth' as it is five scale steps from the root note of a scale, inclusive. Harmonically, we say that the root and octave are close, the root and the fifth less close, and higher integer ratios more distant still. The major and minor scales contain asymmetrically distributed sets of seven notes selected from the twelve. Thus we can also consider stepping from highly harmonic set of three notes (major triad) to the somewhat discordant sound of all seven notes in a scale, to the complete tonal blur that is all twelve chroma in the equal-tempered system played together. These numbers give some possible indication of the cognitive organisation of different grouped percepts.

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
30	Number of distinguishable sounds, moving objects
150	Dunbar's number: number of people in friendship network
3,000	Number of bricks in a normal-sized living room
6,240	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
>250,000,000	Pixels in largest known media multiplicity: video wall

Hundreds Somewhere between 10 and 100 we transition to large numbers, another multiplicities threshold. A popular theory developed by evolutionary psychologist Robin Dunbar [7] states that amongst primates there is a proportional relationship between brain size and group size. The theory predicts the natural group size for humans, the biggest-brained of all primates, to be 150, a figure that has subsequently become known as "Dunbar's Number". This is the number of people our brains can handle maintaining close personal relations with, given the complex demands of social interaction. Of course, humans aggregate in much larger communities, but the thinking about this goes that when we do we do so in a way that does not rely so much on individual ties, instead using methods of imagined community such as religion and nationhood. Such groupings are apparently potentially unbounded.

Thousands Around 1,000 we start to see the possibility for elements to form rich substrates for the production of figures. Minimal effective screen resolution comes in at well under 10,000 pixels. At 96x65, Nokia's 1101 cellphone, the most popular cellphone ever, has only 6,240 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 perfectly enjoyable games.

For the sake of comparison in the audio realm, it makes sense to think of audio resolution in terms of the spectral decomposition of sounds. 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. 1,000s of oscillators will achieve a high definition of reproduction.

Tens and Hundreds of Thousands Likewise, mobile agents also begin to form rich figures in the thousands. We can see these 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, although the Warner Bros cartoon version of this, where a swarm of bees takes on recognisable forms, does *not* occur naturally!

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.

Millions, Billions and Astronomical Numbers The world's largest video wall at the time of writing is the Suntec Singapore "Big Picture", with a resolution of 32,051x7,941, or 254,516,991 pixels, covering an area 15m by 60m [1]. 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, only to the form of the content that can go on it.

The media futures imagined by Hiroshii Ishii consist of 'radical atoms' [10], tiny motile components that form interactive surfaces and collective behaviours. Research in nanotech and micro-scale robotics is contributing to a world where

[1] http://www.dataton.com/stories/watchout-behind-world-record-video-wal

such interactive systems are not only possible but highly feasible, even though for many of us this is still very hard to imagine. But based on existing trends we might reasonably expect advanced media multiplicities, as defined above, with component numbers in the millions and billions. Again, VR media multiplicities already have a head-start in this domain, but are instead constrained by realtime processing limitations, since in this case the processing is centrally managed, if not exactly serial.

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 (Figure 2).

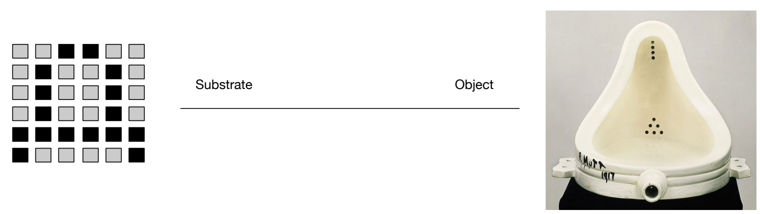

Figure 2: For a substrate, the individual objects act together to present media content, while for a group of objects the significance of the object itself is primary.

We return again to the example of the Spaxels [9], a series of drones, each of which acts as a moving colour pixel. As they presently stand, small in number though they may be, the Spaxels offer a taste of a future in which massive swarms of drones might create impromptu screens in the sky. Literally screens: 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 objects.

Specifically, we see "substrate" here as referring to the complex of technologies and materials required to create *images* (sonic, visual, etc.). Technically when we say that the screen is a substrate, we mean the screen plus all other elements required for the production of the image, such as the computer technology that is driving the screen. A Spaxel screen, like any digitally produced image, still comprises a series of distinct and independent objects: the drones themselves. There is always the capacity to redirect focus onto one or more of these objects alone, rather than the substrate they form. The drones 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.

As we cross modalities, it is clear that there is not really a common model. There is only a shaky equivalence, in the digital case, between this visual example and the world 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 still be more or less focused on the object or on the content being pushed through that object. High-fidelity sound systems promise to make the object invisible, but this ultimately comes down to the listening context and the psychology of listening. For example, a massive subwoofer playing electronically produced sine tones need not be considered a conduit of images, as it is not even attempting to reproduce an original sound world; it simply *is* a sound-making object in the world.

Although we can point to the equivalence between the pixels that make up a digital image and the numeric 'sample' data points that make up a digital audio recording. We don't find any kind of physical manifestation of audio sample data points that combine to constitute the wider image, whereas back in the visual domain, we can shift focus from pixels to screens and back and forth. We can on the other hand declare equivalence between screens as objects and speakers as objects, both being capable of producing images. Likewise, we can consider the question of multi-speaker *spatial* audio, and recognise that as far as *spatial* sonic imagery goes, the multiplicity is key to the creation of the substrate.

We can also think of many sonic experiences in terms of multiplicities of *voices*, such as the instruments of an orchestra or the complex sonic makeup of a rainforest ecosystem. Here, then, we may get closer to an analogy with Spaxels-as-pixels: speakers, instruments and forest animals stand as individual objects (voices) with the potential for a complexity of behaviour in their own right, but under certain circumstances can be seen as coming together to form substrates for greater experiential phenomena; instruments work together to create harmonic and spatial richness. In music, repetitive patterns played by individual voices interleave to form more complex wholes, and the composer plays with the perception of the relationship between the part and the whole by adding and removing elements, or instigating relational transformations. Emergent phenomena can occur in animal vocal communication, like the howling of wolves or monkeys, and in some cases these are argued to have evolutionary functions, grounded in the acoustic phenomena themselves, in creating a sense of group cohesion [5].

Considered as a "voicing device" in a potential chorus, an individual speaker can move between object and substrate in a similar way to a Spaxel. More generally, single objects can form substrates, but *our interest here* lies in situations in which substrates are formed from multiplicities in ways distinct from individual objects. Wherever this occurs it is possible to consider where the multiplicity falls along the axis from objects to substrates, or how it is able to travel along this axis.

Advanced media multiplicities, particularly those which allow autonomous movement of the elements, exhibit the property that we have full control over the movement between objects and substrates. Although not the only way to achieve this, the ability for the elements to move freely is certainly 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 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. A special case of a disordered multiplicity is where the information about the spatial location can be obtained by the parts of the multiplicity, meaning that they can adapt to new locations and present appropriate parts of an image depending on their locations.

3.3 Heterogeneity versus Homogeneity

An even more basic property of a multiplicity is the homogeneity or heterogeneity of the parts that comprise it (Figure 3). To think about homegeneity and heterogenity it is helpful to think through what that means in human terms. In social theory, for example, Durkheim [8] used this to make a distinction between forms of solidarity in different societies. Mechanical solidarity occurred through the homogeneous state of shared tradition, whereas organic solidarity occurred through the interdependencies that arose in complex, structured heterogeneous societies - ‘organic’ here referring to the interdependencies of organs in a body.

As reflection on these social categorisations makes clear, homogeneity and heterogeneity may occur at different levels; humans assume different roles in a society (heterogeneity) despite having essentially identical 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. Pixels may be physically identical, thus interchangeable, but once they are assigned locations on a grid we must honour those positions if we want to use the multiplicity to produce a coherent image. The most elementary form of multiplicity, therefore, is pure homogeneity, meaning that the elements are identical and they also perform the same identical role, exhibiting the same behaviour. We might describe this as a *forest*, in the sense that any distinctions between individual trees are not important to the big picture image. Many light artworks, lacking networks of communication, complex sensors or positioning, take this form. But of course the ability for the elements to change, and therefore to differ *despite* being homogeneous in structure, is an essential property of media.

Next consider a set of elements that is still essentially homogenous but that can be systematically varied. We might describe these as *spectra*. It is common for artists to work systematically through very controlled variations on a very

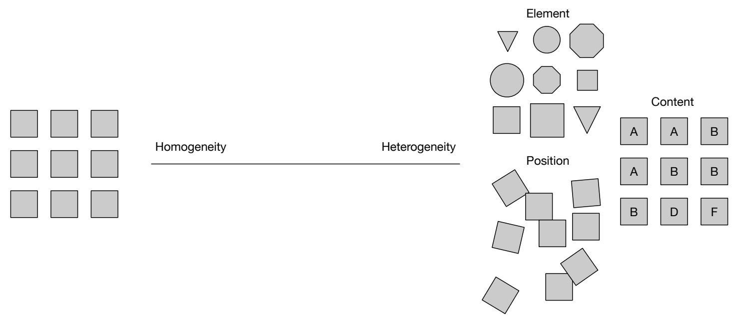

Figure 3: Homogeneity and Heterogeneity – heterogeneity can occur in several main ways.

distinctive theme, and classic examples such as the well-known series works of Mondrian and Rothko come to mind. We also see this clearly in contemporary parametric design, which in fact formalises the process by which a design can be systematically varied. Design elements may be varied for a number of reasons. A typical application is optimisation, whereby the parametric design space becomes a search space for an optimal design. Optimality may be defined in terms of measurable properties or aesthetics as judged by one or more people. In the latter case, the ability to generate and visualise multiple prototypes on a display allows this kind of rapid aesthetic search. In terms of media multiplicities, this is less well-established as a practice, but an indication of the potential exists in the principles of transforming and layering elements in music and visual animation. Examples abound in music, and the definition of variation becomes a somewhat imprecise since any melody can be described as a set of transformations from another melody.

Next in line is a situation in which the elements are heterogeneous, at least in heterogeneous groups, 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. Music again illustrates how the phenomenon might look or sound in the future of media multiplicities, an orchestra combining different groupings of elements, within which there is further variation: brass sounds includes tuba sounds and trumpet sounds, and so on.

The key question here is not whether the system consists of heterogeneous or homogeneous parts, but where aspects of heterogeneity or homogeneity lie in both the design of the system's components and its content.

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 individualistic generative rules (Figure 4).

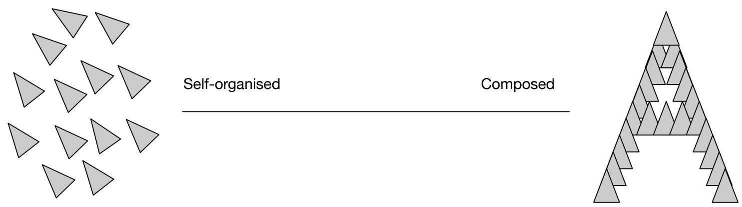

Figure 4: A set of self-organised elements can form flocks and other emergent patterns, while a top-down composed process can create specific structures.

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 structure of the whole is so much more significant than the parts 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 of various types – although we can always come up with scenarios that stand conceptually at least as exceptions, for example in the special 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 system.

An important aspect of this attribute of multiplicities is whether the individual elements interact with each other, and how. 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 (excepting the above exception). They exist in a multiplicity defined as a hub and spokes, rather than a mesh.

In contrast, a self-organised system will often 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 some set of rules. There are many systems of this nature but very few are capable of being used to represent an image or a specific strictly-defined composition as such, and in most cases the way in which the self-organisation results in patterns or behaviours is the central substance of the multiplicity.

4 A Definition 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 quadrophonic sound system count, for example?

In our view, the primary definition of media multiplicities should be based on the substrate-object dimension. Acknowledging also that the distinction is really a matter of degree, we suggest that media multiplicities could also exhibit *radical* 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. The obvious prerequisites are the basic characteristics of digital media, that the device is capable of acting as medium for information, and the existence of multiples.

The more radical the flexibility, the more advanced the media multiplicity. Advanced media multiplicities allow all of their components to move and rearrange, enabling the shift between a media substrate and a set of media objects. They are able to adapt in form so as to achieve heterogeneous form from homogeneous origins. And in their movement and restructuring, they can behave in adaptive and self-organised ways, whilst still enabling creators to design content in a top-down manner.

A problem in defining media multiplicities lies in whether we accept virtual media multiplicities. 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 more real in programming languages than they are in the real world. For now we do not draw a conclusion about how to treat virtual media multiplicities, beyond flagging it as a conceptual problem.

5 Discussion of Examples

In this section, several 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 ideas can be illustrated.

Dialtones, a 2001 work by Golan Levin and collaborators [13], 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 member's 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 was quite clearly a composed work, with both the spatial distribution of the devices and the sounds produced 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. This work, although early, demonstrates the characteristics we have been describing in this paper quite clearly. Similarly, though, it shows that technology limitations were quite significant, to the extent that practical workarounds (using seat number information to allocate ringtones) were necessary for this work to be realised.

Figure 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).

Spaxels [9] are the components of a system built from a set of quadrotors, each outfitted with an RGB LED, and controllable from a central control point. 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 who within a group form a type of 'spectacle'. As a medium or substrate for the transmission of other complex media, their utility is currently limited. Nevertheless theoretically at least, there is no reason why this substrate capability could not be greatly enhanced in future iterations, given that as quadrotors drop in size and increase in capabilities it seems possible that with sufficient numbers the distance between spaxels could decrease so that the eye would be able to resolve them as pixels. Interestingly, 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. 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). This example is significant because it demonstrates the ideas within this framework being employed with quite diverse types of multiplicities.

A very similar system, a set of quadrotors with centrally controlled behaviour and onboard lighting, is the *Sparked* work of Cirque du Soleil. Despite sophisticated and precise computer control that enables precise co-operation the focus is not on using the elements as a substrate 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, rather than their behaviour together to produce images.

DIADs [4, 3] are 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 the devices can act as a self-organising unit. They are conceived of, and currently implemented as, homogenous device groups made up of 20cm diameter ball-like shapes.

Siftables [18] (Figure 6) are a set of small reconfigurable battery-powered devices which contain both a display and computing capabilities, and are shaped like a scrabble piece (although slightly larger)[2]. They can be used to develop applications that exploit the physical manipulation skills users have developed from childhood - especially relating to board games such as scrabble or dominos. In the context of the framework discussed, this would be described as largely a 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 other media, and indeed there are substrates of this type that have been demonstrated. Similarly, the networking capabilities of these devices mean that the media designed for the system could well be composed - that the system's reaction to interaction could be rendered negligible, with the output devoted entirely to the content developed by the composer. Of course it is more likely that a system of this nature would be better suited to an interactive program or game (loaded onto the system) rather than to be used as a display for a composed work.

Ocean of Light, by Squidsoup (Figure 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

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

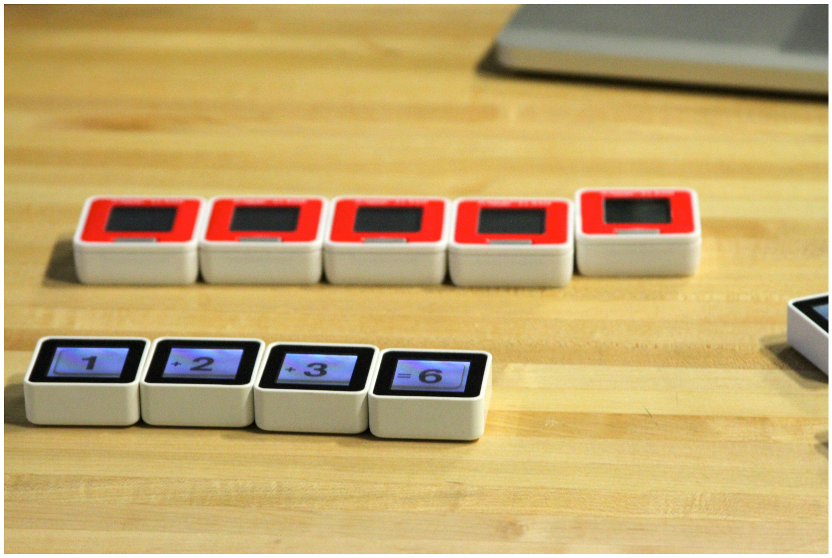

Figure 6: Siftables are a set of small reconfigurable battery-powered devices which contain both a display and computing capabilities, and which exploit tangible interaction methods. Image Copyright J. Nathan Matias (Attribution-ShareAlike CC BY-SA 2.0).

space. This system is nearly perfectly homogenous and forms a substrate for other media images and effects, but as soon as a performer or audience member is in the space, the system can be physically perturbed and then takes on a physical role as a set of objects. Custom software allows for the colour and brightness of each light to be controlled, meaning that the system can act as a substrate for media presentation, and can also be synchronised to electroacoustic audio content.

In Table 5 we review more examples of artworks and systems described using our axes of description.

Table 2: A number of examples of artworks (both interactive and non-interactive) and their relationship to the description axes.

Name	Creator	Year	Description	Quantity	Substrate/ Object	Composed/ Self-Organised	Heterogeneous/ Homogeneous
186 prepared dc-motors, cotton balls, cardboard boxes 60x60x60cm	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 choroegraphed 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 elements and content
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
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
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 Devices, Heterogenous Content
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 1,000 variations of the musical content were produced systematically.	1000	Objects	Self-organised	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

Table 2: A number of examples of artworks (both interactive and non-interactive) and their relationship to the description axes.

Name	Creator	Year	Description	Quantity	Substrate/ Object	Composed/ Self-Organised	Heterogeneous/ Homogeneous
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	Self-organised	Homogenous
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 Völker	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 Völker	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

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 define 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 quite advanced. Their behaviour is sometimes centrally *composed* or directed, and in other cases defined along *self-organised*, rule based behaviours. Finally, the number of elements in the group is necessary to understanding the way in which the elements of the group are perceived, as opposed to how the group itself is perceived.

This is an important step as there is a need to distinguish these defining properties and affordances, which suggest a radically new form of media in their coming together (if not each on their own) and increasing sophistication. 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 substrates, to use fixed composed works and sets of homogenous devices, often with homogenous content. As technology progresses, dynamicity in these dimensions has increased; multiplicities can now easily incorporate elements with self-organising capabilities (general purpose CPUs), can incorporate heterogeneity amongst devices, and can act as both object and substrate.

As these capabilities become more widespread, the development of creative production techniques will be of particular interest for this field, for which 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 with ease.

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, which means that many examples of media multiplicities are automatically borderline and stand as precursors to what we feel will be the real deal. Related to this, there is the special case of media multiplicities existing in Virtual Reality, which are an ambiguous case, since many of the physical challenges of creating physical media multiplicities do not apply, but conceptual challenges remain.

7 Conclusion

In this paper we have discussed concepts that can be used to understand and describe media multiplicities. These factors suggest radical new modes of media experience and production. We feel that the axes we have proposed help to establish valuable terminology and a conceptual framework for thinking about media in this new era.

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