Vaughan, Josephine; Ostwald, Michael J. Measuring the geometry of nature and architecture: comparing the visual properties of Frank Lloyd Wright's Fallingwater and its natural setting. Published in *Open House International* Vol. 47, Issue 1, p. 51-67 (2022).

**Available from**: http://dx.doi.org/10.1108/OHI-01-2021-0011

Vaughan, J. and Ostwald, M.J. (2022), "Measuring the geometry of nature and architecture: comparing the visual properties of Frank Lloyd Wright's Fallingwater and its natural setting", *Open House International*, Vol. 47 No. 1, pp. 51-67. https://doi-org.ezproxy.newcastle.edu.au/10.1108/OHI-01-2021-0011
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# Measuring the geometry of nature and architecture: Comparing the visual properties of Frank Lloyd Wright's *Fallingwater* and its natural setting

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**Abstract**

Purpose

Frank Lloyd Wright's famous house *Fallingwater*, has been the subject of enduring scholarly debate centred on the allegedly clear parallels between its form and that of its surrounding natural setting. Despite these claims being repeated many times, no quantitative approach has ever been used to test this argument. In response, this paper uses a quantitative method, fractal analysis, to measure the relationship between the architecture of *Fallingwater* and of its natural surroundings.

Methodology

Using fractal dimension analysis, a computational method that mathematically measures the characteristic visual complexity of an object, this paper mathematically measures and tests the similarity between the visual properties of *Fallingwater* and its natural setting. Twenty analogues of the natural surroundings of *Fallingwater* are measured and the results compared to those developed for the properties of eight views of the house.

Findings

Although individual results suggest various levels of visual similarity or difference, the complete set of results do not support the claim that the form of Frank Lloyd Wright's *Fallingwater* exhibits clear visual similarities to the surrounding landscape.

Originality

In addition to testing a prominent theory about Wright's building for the first time, the paper demonstrates a rare application of fractal analysis to interpreting relations between architecture and nature.

**Key Words:** Frank Lloyd Wright; Organic architecture; Nature and architecture; House and landscape; Fractal analysis; Fractal dimension; Landscape; Architecture; Environmental design; Fallingwater

## 1 Introduction

*Fallingwater* is an iconic three-storey house set over a waterfall in a forested valley in Pennsylvania (USA). Designed by Frank Lloyd Wright in the 1930's for the Kaufmann family, *Fallingwater* is one of the most famous houses in the world today. The approach path taken by visitors to *Fallingwater* immerses them in nature, channeling them through a thickly forested glade above the Bear Run creek. At the end of the path, the valley opens out revealing the house, like something that has grown out of its site (McCarter, 1999). Broad concrete horizontal outdoor spaces are layered around the core of the house, projecting beyond the rising walls of rough-cut stone which enclose small private rooms. Dramatically, the waters of Bear Run travel under the house and then emerge from beneath the living room terrace, pouring down a series of ledges and flowing out of the west of the site.

Today, Wright's architecture is often described as reflecting its natural site, and many scholars argue that *Fallingwater* is Wright's consummate demonstration of the close visual connection between the landscape and a building (Hoffmann, 1993; Kaufmann, 1986; Levine, 1996). For example, *Fallingwater* has been described as a place that 'effectively unites architecture and nature as one' (Laseau and Tice 1992, p. 94). Despite such claims, there are those who disagree, prompting an ongoing debate. For example, Frampton argues that *Fallingwater's* purpose is to 'juxtapose nature and culture as explicitly as possible' (1994, pp. 72). This debate about the visual similarities of *Fallingwater* and its site is the catalyst for this paper. However, rather than revisiting the past arguments in detail, this paper takes a quantitative, computational approach. Such approaches are significant because, as Laseau and Tice argue (1992, p. ix), Wright's work has been extensively examined using *qualitative* methods, but only a relatively small number of *quantitative* studies have been published. Such studies do, however, confirm that new insights into Wright's architecture can be developed using computational means to illuminate the arguments of historians. Examples of quantitative studies of Wright's architecture include those employing diagrammatic analysis (MacCormac, 2005; Sergeant, 2005), shape grammars (Knight, 1994; Koning and Eizenberg, 1981; Lee *et al*., 2017), typological studies (Laseau and Tice, 1992), space syntax (Behbahani *et al*., 2014; 2016) and isovist fields (Dawes and Ostwald, 2014; Ostwald and Dawes, 1998).

Possibly the most common computational method that has been used for measuring the properties of Wright's architecture is fractal dimension analysis. This method measures the characteristic visual complexity of images, particularly line drawings. Fractal analysis was first applied to Wright's architecture by Bovill (1996), who analysed Wright's *Robie House,* and it has since been used by multiple researchers to examine Wright's work (Lorenz, 2003; Ma *et al*., 2020; Sala, 2000; Wen and Kao, 2005). The most extensive application of fractal analysis in architecture measured and compared the properties of 85 houses, 15 of them by Wright (Ostwald and Vaughan, 2016). Significantly, none of the past research using fractal analysis examines *Fallingwater*. There is another reason why fractal analysis is relevant in the present context, it has been used to the compare the visual complexity of both buildings and landscapes (Bechhoefer and Appleby, 1997; Bovill, 1996; Lorenz, 2003).

The present paper uses computational fractal analysis to test if the formal and visual properties of Wright's *Fallingwater* strongly reflect aspects of its natural setting. The paper commences with a review of Wright's claims, and historians' arguments about the alleged connections between the form of *Fallingwater* and that of its site. Through this review, four key points of comparison are identified, providing the basis for constructing a mathematical examination of the arguments. Thereafter, the paper introduces fractal analysis, describing its background, application and results. The fractal analysis approach in this paper uses the most advanced architectural method and software, coupled with insights drawn from the recent framework for comparing architecture and nature (Vaughan and Ostwald, 2017). Drawing on the framework, the paper presents the results of an analysis of 20 analogues of the natural landscape surrounding *Fallingwater* and of eight views of the house. This is followed by a discussion of the results and what they imply about the visual connection between *Fallingwater* and its setting. Methodological limitations are described throughout and are also considered in the discussion.

## 2 *Fallingwater* and Nature

Liliane and Edgar Kaufmann were introduced to Frank Lloyd Wright by their son, Edgar Junior in 1934. The Kaufmanns, who shared many of Wright's philosophical views about the value of spending time in nature (Cleary, 1999), had a holiday cabin located in a thickly forested area of Pennsylvania, adjacent to Ohiopyle State Park and Bear Run Nature Reserve, within the lands of the Monongahela, Delaware, Shawnee, and Seneca (Palmer, 1984). The Kaufmanns' property was 'a wooded glen […] characterized by large sandstone outcroppings that exhibited a rustic, even ancient, appearance' (Smith, 2000, p. 21). The land itself was also full of life, with a dense forest canopy above of 'red maple, oak black cherry, tulip poplar, and black birch' and below the 'shrubs are evergreen, including mountain laurel and rhododendron' (Cleary, 1999, p. 38). On the forest floor there was a 'rich mat of ferns and mosses and a variety of wild roses, mountain roses, and native bulbs' (Cleary, 1999, p. 38). The Bear Run stream entered the Kaufmanns' property from the east, running through a valley of the ancient Pottsville sandstone, creating waterfalls as it flowed out of the west of the site to the Youghiogheny River.

When the Kaufmanns began thinking of building a more refined holiday home, they invited Wright to inspect the site, which he did in December 1934. Edgar Kaufmann Junior recalls the day Wright came to their site when the 'mountains put on their best repertoire to him – sun, rain and hail alternated; the masses of native rhododendrons were in bloom' (1983, p. 69), and he remembers how the weather that day 'accentuated the rugged terrain' (1986, p. 36). After showing Wright the site they had chosen for the house, the Kaufmanns took Wright to a special location in the creek where they loved to swim, and the rock that they enjoyed sunbathing on. After staying all day on the property, Wright requested 'a survey of the terrain around the falls [asking that] large boulders and large trees were to be marked on it' (Kaufmann, 1983, p. 69). In September 1935 the Kaufmanns saw Wright's design for the first time, and were surprised that he had located the house directly over the waterfall at Bear Run, on their favoured swimming spot. They agreed to the concept design in September and the first working drawings were completed in January 1936 (Langmead, 2009). Construction of *Fallingwater* commenced in June of 1936 and the house was completed by the end of 1937.

From the earliest accounts, *Fallingwater* has been discussed by architectural critics in terms of its connection to nature (Mumford, 1938), and Wright himself described it as 'an extension of a cliff beside a mountain stream' (Wright, 1938, p. 36). Subsequent descriptions of *Fallingwater* have noted that it is a building which displays an 'unparalleled integration of architecture and nature' (Levine, 2005, p. 250). Prior to *Fallingwater's* design, Wright was already known for creating links between natural and architectural forms and his design strategies for creating these reflections are well documented, including a clear interest in the geometry of the landscape.

One of the key design strategies Wright used in the 1930s commenced with the identification of the characteristic natural shapes of a site via its topography, ecology and geology which he then reinterpreted in the built form (De Long, 1996; Jodidio, 2006). Wright used this strategy at *Fallingwater*, whereby he initially identified the 'unique characteristics of the site' (Riley, 1994, p. 104). But thereafter, disagreement exists about the extent to which Wright used these natural forms. Scholars, and Wright himself, have identified four natural elements which allegedly generated *Fallingwater's* appearance. These are: the Pottsville sandstone geology (Fell, 2009; Hoffmann, 1986; Kaufmann, 1986; Levine, 2000; Wright in Meehan, 1984), the gully (Andropogon, 1997; Kaufmann, 1986; Wright, 1994), the forest (Fell, 2009; Levine, 2000; Wright, 1938), and the Bear Run stream (Cleary, 1999; Hoffmann, 1986; Levine, 2000; Smith, 2000; Wright, 1938).

Wright himself described the shape of the Pottsville Sandstone formation as a major influence on the design of *Fallingwater*. He observed that just as '[n]ature cantilevered those boulders out over the fall … I can cantilever the house over the boulders' (Wright, qtd in Levine, 2000, p. 37). Following this lead, scholars have accepted that a level of visual similarity exists between the site's sandstone geomorphology and the building's appearance, several proposing that the house's forms visually recall the form of the site, albeit in an understated or abstracted way. For example, Fell suggests that the *Fallingwater's* terrace 'echoes the geometry of the moss-and lichen-covered cliff' below it (2009, p. 11), and for Kaufmann, '[l]ayered stone outcroppings are features of the terrain, their character echoes in the stone walls of the house and in the rippled flagging that covers its floors' (1986, p. 124). For Levine, '[t]he horizontal lines of the stone walls of the house [...] echo the strata of stone ledges in the walls of the glen' (Levine, 2000, p. 61).

An alternative argument, proposed by architectural historians and critics, emphasises Wright's decision to locate *Fallingwater* within the steep 'dramatic gorge' of the Appalachian plateau (Andropogon, 1997, p. 37), suggesting that this valley shaped the building's form. Edgar Kaufmann even argues that the 'major relationship of the house and site arises from setting the building within the valley' (1986, p. 124) and Wright's own description of *Fallingwater* highlights the valley: 'a design for living down a glen in a deep forest' (Wright, 1938, p. 41).

Wright's 'deep forest', a 'typical successional Mesophytic Forest' (Andropogon, 1997, p. 27) which envelopes *Fallingwater* (Fell, 2009, p. 88), is the third natural feature that critics claim is mirrored in the forms of the building. Wright even integrated the living trees of the forest into the building, and the poplars within the entry trellis have a similar 'rugose texture and dark color' to that of the adjacent 'wall and thus appeared to be one in nature with it' (Levine, 2000, p. 61). Scholars also note that the form and texture of the forest has shaped that of the building. For example, Levine observes that the long narrow columns of stone on the eastern facade 'merge into the background of tree trunks' (2000, p. 64).

The last of the four natural features is the Bear Run waterfall and its ledges. Wright described *Fallingwater* as a house that comes '[o]ut of the stone ledges over the stream' (Wright, 1938, p. 36). Hoffmann (1986) and Levine (2000) argue that the shape of the waterway influenced the form of *Fallingwater*, and Smith proposes that the house 'mimic[s] the form of the waterfalls in the building' (2000, p. 25). Levine agrees, declaring specifically that it is 'the trays, with their upturned, rounded edges, [that] read as [...] the overflowing pools of a cascading fountain' (2000, p. 55).

While the most common scholarly view is that *Fallingwater* reflects the surrounding landscape, alternate arguments have also been presented. For example, Hoffmann reflects that '[a]lthough he meant to honor the forest site, Wright also chose to compete with the high drama of the falls and with the insistent asymmetric rhythms of the projecting sandstone ledges and long cantilevered leaves' (1995, p. 83). Similarly, Aguar and Aguar feel that the house is 'an architectural intrusion' that 'contradicts every dictum [Wright] ever expressed with respect to site integrity or harmony with nature. Indeed, *Fallingwater* overwhelms nature' (2002, p. 230). In a similar way, Alofsin describes *Fallingwater* as a 'metaphorical interpretation of human confrontation with nature' (1994, p.46) and Spirn argues that Wright left the natural landscape of *Fallingwater* untouched to deliberately create a juxtaposition with the building (Spirn, 1996).

In all of these arguments – both for and against the proposition that *Fallingwater* has a similar visual character to its natural setting – qualitative connections between architecture and nature are made using language. In contrast, this paper uses one of very few methods available to mathematically measure and compare the characteristic complexity of diverse objects; computational fractal analysis.

## *3.* Fractal Dimension Analysis

Originally proposed by Mandelbrot (1975; 1977; 1982) as a means of rigorously measuring roughness and irregularity in natural forms, a fractal dimension ($D$) is a measure of the space-filling properties of an image or object. It provides a numerical value that reflects the volume and distribution of geometry or information in the subject being measured. In an image, for example, $D$ will be between one and two ($1.0 > D > 2.0$), or conceptually, the subject of the image will be greater than one-dimensional, but not quite two-dimensional.

The most common approach to measuring the fractal dimension of an image is the 'box-counting' method (Mandelbrot, 1982; Ostwald, 2013). This method commences by placing a grid over the image being measured, and then each square is examined to identify if any of the lines of the image are contained therein. The number of boxes which have lines in them is noted. Next, a smaller grid is overlaid on the image and the process is repeated, and the number of boxes containing lines is also noted. A mathematical comparison is then constructed between the number of boxes with lines in the first grid and in the second grid, by plotting a log-log diagram (Bovill, 1996). The slope of the log-log graph is the 'box-counting dimension' of the image. When multiple additional grid comparisons are graphed, the slope of the line begins to approximate $D$. Past research has identified optimal settings for the application of the box-counting method, including number of grids, the scaling coefficient (ratio between grids), image size, position, resolution and representation (Ostwald, 2013; Ostwald and Vaughan, 2016). Furthermore, calculations are sensitive to the content of the image that is selected for analysis (what will be expressed of the *subject*) and to its representation (how the subject is *presented*) (Ostwald and Vaughan, 2012; Zarnowiecka, 2002). To develop a rigorous and repeatable result requires a consistent logic to both the subject and its presentation. Once this is achieved, then comparisons between $D$ results may be constructed using range ($R$) or difference been results, which is often expressed as a percentage. While numerical analysis of $R$ values is central to framing a comparison, past research has also described $R$ using indicative qualitative descriptors found in many papers. Using qualitative descriptors, a range below 2.0% could be described as 'indistinguishable'; a range of $2.0 \leq x < 6$ as 'very similar'; a range of $6 \leq x < 11$ as 'similar'; $11 \leq x < 20$ as 'comparable' and a range of over 21% as being 'unrelated'. These provide an intuitive way of comparing results, even though it is likely they over-emphasise the visual similarities because early research tended to use less accurate calculations (Ostwald and Vaughan, 2016).

Fractal analysis has previously been used to measure architectural designs (Lionar and Ediz, 2020; Ma *et al*., 2020; Ohuchi *et al*., 2020) and natural forms (Liang *et al*., 2013; Patuano and Tara, 2020; Wang *et al.,* 2011). Importantly, there are examples where researchers have compared fractal dimensions of nature and architecture (Boldt, 2002; Burkle-Elizondo and Valdéz-Cepeda 2006; Nakib, 2010; Zarnowieka, 1998). For example, Bovill (1996) compared the fractal dimensions of a vernacular facade and of a nearby natural land form in Amasya, Turkey. He concluded that both had similar levels of visual complexity and thus, the topography must have either influenced the design of the buildings, or alternatively all of these features were shaped by larger environmental conditions. Some of these comparisons have, however, subsequently been mathematically measured and compared with mixed results (Lorenz, 2003; Vaughan and Ostwald, 2009; Bourchtein *et al*., 2014). The predominant difficulty has been that the analytical subjects (the image content) and their presentation (the lines or data in an image that are chosen for analysis) are inconsistent (Bourchtein *et al*., 2014; Vaughan and Ostwald, 2017; Zarnowieka, 1998). For example, comparing $D$ for a silhouette of a mountain range, and $D$ for the plan of a building, would be a poor choice of image *subject*, unless an architect explicitly described the plan as being shaped like the mountain silhouette. Similarly, comparing $D$ for a photograph of a tree, and $D$ for a line drawing of an elevation, would be a poor choice of *representation*, as photographs and line drawings are processed differently in fractal dimensional analysis. The technical solution is to ensure that the natural and architectural subjects, their representations and data, are consistent and reasoned (Vaughan and Ostwald, 2017). Importantly, a comparison between nature and architecture is only reasonable if the natural and architectural data subjects and representations could be considered analogous (Vaughan and Ostwald, 2017). This is the approach adopted in the present paper, to select the images for analysis based on coherent subjects, presentation and data type.

## 4 Application and Data Source

Four steps are required before commencing analysis. The first is to identify the forms, natural and architectural, which historians, critics or Wright himself have explicitly linked together. These provide analytical subjects that have a logical basis for comparison. For the present paper these are the Pottsville sandstone, the Mesophytic forest, the steep gully and Bear Run stream. For the house, these are its iconic views (perspectives or photographs) and its plan. Thus, four natural features and two aspects of *Fallingwater* provide logical subjects for comparison.

The next step is to identify appropriate levels of presentation or representation between compared subjects – not only in their physical representation (a photograph or line drawing for example) but also in their data type (a site plan or perspective drawing, for example). The most robust and repeatable representation format for this purpose is the line image (Bovill, 1996; Lorenz, 2003; Ostwald, 2013), and it has also been the subject of detailed testing, standardisation, and validation for fractal dimension calculations (Ostwald and Vaughan, 2016). Line drawings are most appropriate for analysing general design issues, where 'design' is taken to encompass decisions about form and changes in materiality, which are the main elements scholars use to describe *Fallingwater* in relationship to the landscape. The level of representation chosen for both architecture and nature is single line tracing (no textures or infills), representing changes in form or surface level of greater than 25 mm, or between materials.

The third step involves determining which image views are most appropriate for comparison. Taking into account the need to produce an analogous condition (Vaughan and Ostwald, 2017), this paper uses two correlations. The first compares *views* of the local natural objects (images of 3D objects, converted into 2D line drawings) with *perspective views* of the house (images of the house converted into 2D line drawings). The second compares *plans* (2D line drawings) of the local natural objects with *plans* (2D line drawings) of the house.

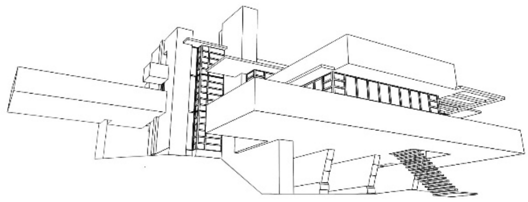
The fourth step is to prepare the images for analysis. The images of natural subjects are derived from edge-detected photographs ('linear detail extraction') in neutral lighting conditions (no strong shadows) and the matching images for views of *Fallingwater* are line drawings of Wright's architectural perspectives (which were widely published at the time and also reflect the major photographs that were available). Four perspective views of *Fallingwater* are compared with four views each of the four natural elements, producing twenty views for comparison. In plan, the natural subjects are represented by line-drawn plans (technical site drawings), and *Fallingwater* is represented by a line-drawn architectural plans. Four plans of *Fallingwater* (from the ground floor to roof terrace) are compared with one plan each of the natural elements, producing eight plans for comparison.

Table 1 summarises all the terms and codings used to describe the results for this research. For this paper, $D$ was calculated using *ArchImage* (Version 1.16) software. The images were prepared for analysis in accordance with the pre-processing standards used in this field, including image position, line weight, white space and image depth which are all standardised using Photoshop (Adobe) prior to importing the files into *ArchImage* for analysis. (Ostwald and Vaughan, 2016).

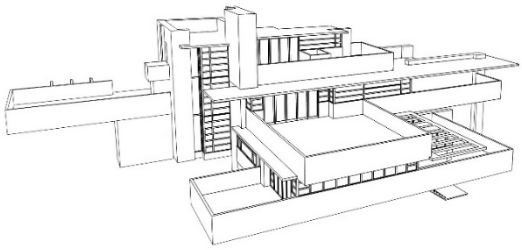
*Table 1 Summary of definitions relating to the analysis of an individual house*

| Abbreviation | Meaning | Explanation |
|---|---|---|
| $D$ | Fractal Dimension | Fractal dimension ($D$) is a measure of the formal complexity of a design and the consistency with which it is distributed across all scales of a design. |
| $D_V$ | $D$ for a specific *view*. | The fractal dimension of the perspective view of an object is $D_V$. The fractal dimension of a plan is $D_P$. |
| $D_P$ | $D$ for a specific *plan*. | |
| *Set* | Collection of related values | All of the images for one natural element are considered a 'set' while all the *Fallingwater* images are another 'set' |
| $\mu_V$ | Mean $D$ for the views of a set. | A 'mean' is the average of a set of values (the sum of the values divided by their number). It is expressed here as a 'population' mean ($\mu$) because the findings of this research are generally not extrapolated to comment on anything other than the actual images being analysed. The mean $D$ for all of the views is $\mu_V$. This value reflects the typical level of characteristic formal complexity visible. |
| $\mu_P$ | Mean $D$ result for the habitable plans of a building. | The mean $D$ for all of the plans of *Fallingwater* is $\mu_P$. This value reflects the typical level of characteristic complexity present in the spatial and formal properties of the interior and the expression of its roof. There is only one plan for each natural element so the mean $D$ is not calculated for these. |
| $R$ | Range | Difference between two fractal dimensions. |

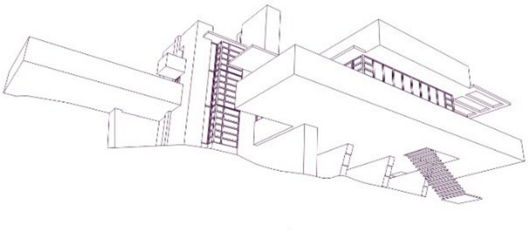
The four perspective views were generated from a CAD model based on Wright's original drawings reproduced by Drexler (1965) and Futagawa and Pfeiffer (1987c; 2003). The angles for the perspective views (fig. 1 a-d) replicate the vanishing points of Wright's original drawings. These images depict the house from three distinct angles with the other being a slight variation of Wright's oft-published colour-rendered perspective view of the house from below. The plans for *Fallingwater* are traced from those published by Storrer (2006), Futagawa and Pfeiffer (1986). The plans do not depict doors, glazing elements or built-in furniture (fig. 1 e-h) in accordance with representations standards for this method.



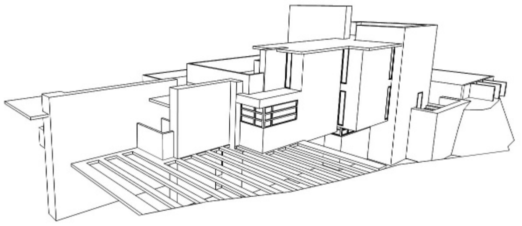
*a. View 1*



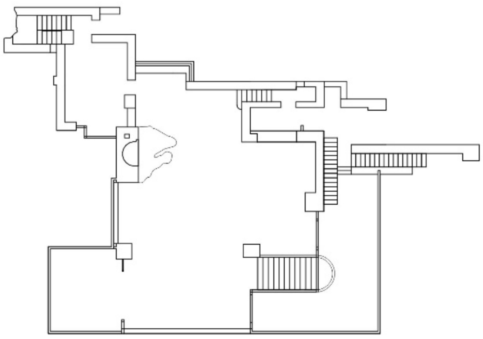
*b. View 2*



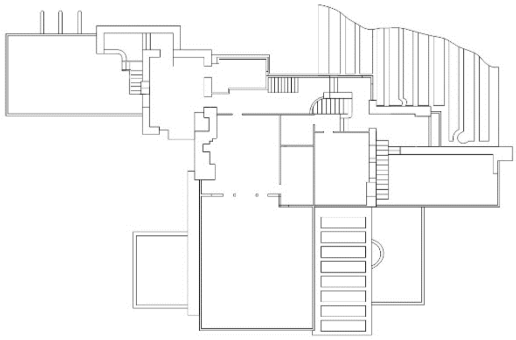
*c. View 3*



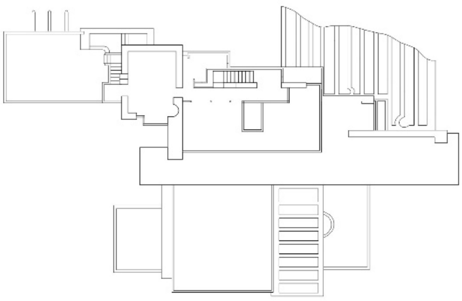
*d. View 4*



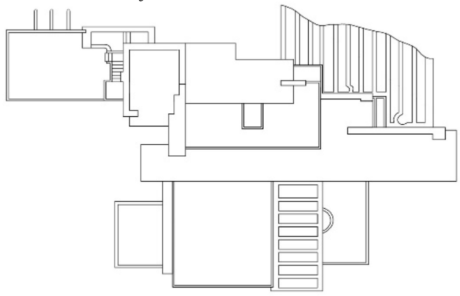
*e. Ground Floor Plan*



*f. First Floor Plan*



*g. Second Floor Plan*

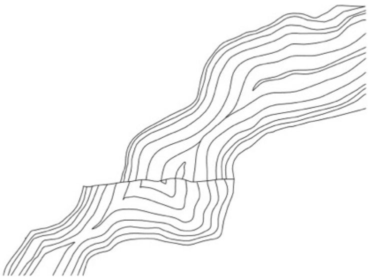


*h. Roof Plan*

*Figure 1 a – h Images of* Fallingwater *analysed – Level 3 representation, not shown at a uniform scale*

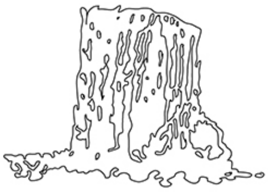
The views and plans of the natural elements analysed in this paper are all derived from the immediate surroundings of *Fallingwater*. The area used for the natural element selection is based on the site plan prepared by Wright's apprentices (Kaufmann, 1986: 39). This plan was produced in Wright's studio from the original survey site plan prepared for Kaufmanns (McCarter, 2002: 5).

For each natural element, four line-drawn representations were made of a unique example on the site and the images of natural views produced for analysis are depicted in Figure 2. The site plan is separated into four layers, each only showing the individual element analysed: the rocks, the contours, the watercourse and the tree cover (Fig. 2). Wright's version of the site plan contains some minor errors and omissions that might affect the analysis, including the position of the waterline and the tree canopies, but no attempt has been made to correct these for the present research. The claims about *Fallingwater* and nature are largely about Wright's intentions and so the information available to Wright at the time, and which has been published since then as proof of various claims, is prioritised. Except for the views of the valley, the views of the natural elements are edge-detected line drawings extracted from 2012 photographs of the landscape surrounding *Fallingwater*. The views of the valley were generated using Google Earth.

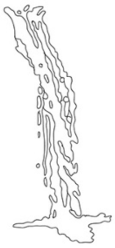


*a. Water plan (Wright's survey plan)*

*b. Water view 1*

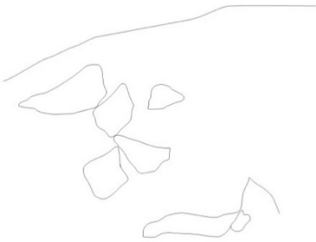


*c. Water view 2*



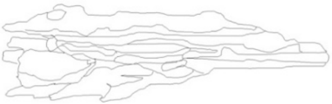
*d. Water view 3*

*e. Water view 4*

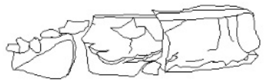


*f. Rock plan (Wright's survey plan)*

*g. Rock view 1*

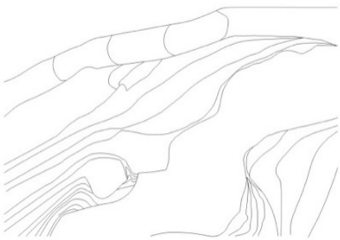


*h. Rock view 2*

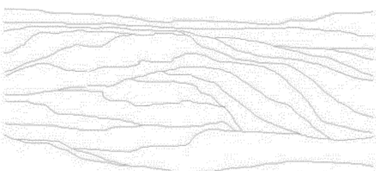


*i. Rock view 3*

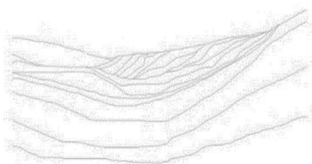
*j. Rock view 4*



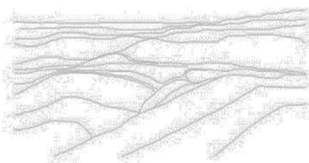
*k. Valley plan (Wright's survey plan)*



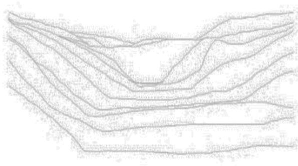
*l. Valley view 1 (north)*



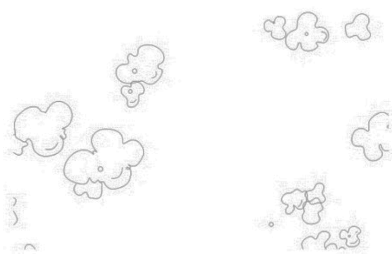
*m. Valley view 2 (east)*



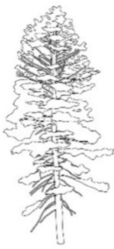
*n. Valley view 3 (south)*



*o. Valley view 4 (west)*



*p. Tree plan (Wright's survey plan)*



*q. Tree view 1 (eastern hemlock)*

*r. Tree view 2 (scarlet oak)*

*s. Tree view 3 (tulip poplar)*

*t. Tree view 4 (great laurel rhododendron*

*Figure 2 Images of natural elements analysed – not shown at a uniform scale*
*Water(a-e); Rocks (f-j); Valley (k-o); Trees (p-t)*

## 5 Results

The cardinal directions from which the perspective views are predominantly framed are from the south and south-west (looking towards the north and north-east), with only one perspective view from the north (looking south towards the side of the house facing the steep slope behind). This northern perspective has the highest fractal dimension result of the perspective views of the house ($D_{V4}$ = 1.5170). Of the southern perspectives, the treetop view looking down onto the southern balconies from above has the second-highest result ($D_{V2}$ = 1.5140), which is quite close to that of the northern perspective. The two views looking up from the water of Bear Run at the southern facade of the house vary only slightly in their perspectival construction, and their results are also relatively similar ($D_{V1}$ = 1.4474 and $D_{V2}$ = 1.4354). With a view predominantly of the underside of the outdoor terraces, these two perspectives lack the volume of geometric detail found of the other perspectives and thus have the lowest fractal dimensions. Overall, the mean result for the perspective views is $\mu_V$ = 1.4785 (table 2 and Fig. 3).

Of the floor plans of *Fallingwater*, the ground floor has the lowest fractal dimension ($D_{P0}$ = 1.3540). Without the furniture and the doors leading to the outside spaces, this floor becomes a shelf-like open area. The first and second floors are the most complex plans in the house ($D_{P1}$ = 1.4291 and $D_{P2}$ = 1.4018). Due to the terrace overhangs and outdoor circulation which are all visible in the roof plan, the roof plan of *Fallingwater* is ($D_{PR}$ = 1.3845) and is close to the mean result of all the plans ($\mu_P$ = 1.3923).

The range for the perspective views is $R_{V\%}$ = 8.16 which suggests that, compared to each other, the perspective views are visually 'similar' (Ostwald and Vaughan, 2016). For the plan results, the range is slightly closer, $R_{P\%}$ = 7.51, and these could also be described as visually 'similar'.

*Table 2 Results for* Fallingwater, *perspective views ($D_V$) and Plans ($D_P$) and Natural elements, views ($D_V$) and Plans ($D_P$): SD is the Standard deviation of the view data.*

| ***Fallingwater*** | | *House* | | | |
|---|---|---|---|---|---|
| Views | $D_{V1}$ | 1.4474 | | | |
| | $D_{V2}$ | 1.5140 | | | |
| | $D_{V3}$ | 1.4354 | | | |
| | $D_{V4}$ | 1.5170 | | | |
| | $\mu_V$ | 1.4785 | | | |
| | $R_{VD}$ | 0.0816 | | | |
| | $R_{V\%}$ | 8.1600 | | | |
| Plans | $D_{P0}$ | 1.3540 | | | |
| | $D_{P1}$ | 1.4291 | | | |
| | $D_{P2}$ | 1.4018 | | | |
| | $D_{PR}$ | 1.3845 | | | |
| | $\mu_P$ | 1.3924 | | | |
| | $R_{PD}$ | 0.0751 | | | |
| | $R_{P\%}$ | 7.5100 | | | |
| ***Natural Elements*** | | *Water* | *Rocks* | *Valley* | *Tree* |
| Views | $D_{V1}$ | 1.6532 | 1.5450 | 1.3200 | 1.5699 |
| | $D_{V2}$ | 1.5985 | 1.5450 | 1.3169 | 1.4176 |
| | $D_{V3}$ | 1.4198 | 1.4744 | 1.3180 | 1.4142 |
| | $D_{V4}$ | 1.5840 | 1.2928 | 1.3109 | 1.7316 |
| | $\mu_V$ | 1.5639 | 1.5215 | 1.3165 | 1.5333 |
| | $R_{VD}$ | 0.2334 | 0.0706 | 0.0091 | 0.3174 |
| | $R_{V\%}$ | 23.3400 | 7.0600 | 0.9100 | 31.7400 |
| | *SD* | 0.1005 | 0.7614 | 0.0039 | 0.1508 |
| Plans | $D_P$ | 1.4671 | 1.1630 | 1.3378 | 1.1787 |

The views of the water are taken from four different photographs of the waterfalls created by the rock shelf in the Bear Run stream. Of these, the main drop, during heavy rains or after the snow has melted, creates a wall of falling water, parallel to the southern facade of the house and the image of this fall has the highest visual complexity of all the water images ($D_{V1}$ = 1.6532). The least complex water image is of the same waterfall, but from a line drawing extracted from a photograph taken when there was a lower water level in the Bear Run stream ($D_{V3}$ = 1.4198) (Table 2).

Of the tree views, the Great Laurel Rhododendron has the highest fractal dimension ($D_{V4}$ = 1.7316) this is also the highest dimension of all of the natural views analysed. The other evergreen tree analysed, the Eastern Hemlock, has the second highest dimension ($D_{V1}$ = 1.5699), this is the expected result, as the leaves add visual detail to the images. The deciduous trees, the Scarlet Oak ($D_{V2}$ = 1.4176) and the Tulip Poplar ($D_{V3}$ = 1.4142) have a similar result to each other, but lower than the evergreens.

The four large rock outcrops analysed are all examples of the Pottsville Sandstone found in the Bear Run creek bed or near the house. The results for the first two are interesting because they have the same fractal dimension ($D_{V1}$ = 1.5450; $D_{V2}$ = 1.5450). These two may also be outcrops of the same rockface: the view 1 rock is the large outcrop that supports the western terrace of the house, and the view 2 rock is of the cliffside along part of the stream, below the western terrace. Those two have the highest complexity of the four rocks analysed. The next most complex section of rock is the cliffside underneath the southern terraces of the house ($D_{V3}$ = 1.4744), a result not too dissimilar to the others. The least complex result is for a group of boulders that sit mid-stream, just below the house ($D_{V4}$ = 1.2928). Perhaps because they are subject to continual water erosion, they are less fissured than the cliff edges or the boulders above the water level, hence they have a lower fractal dimension.

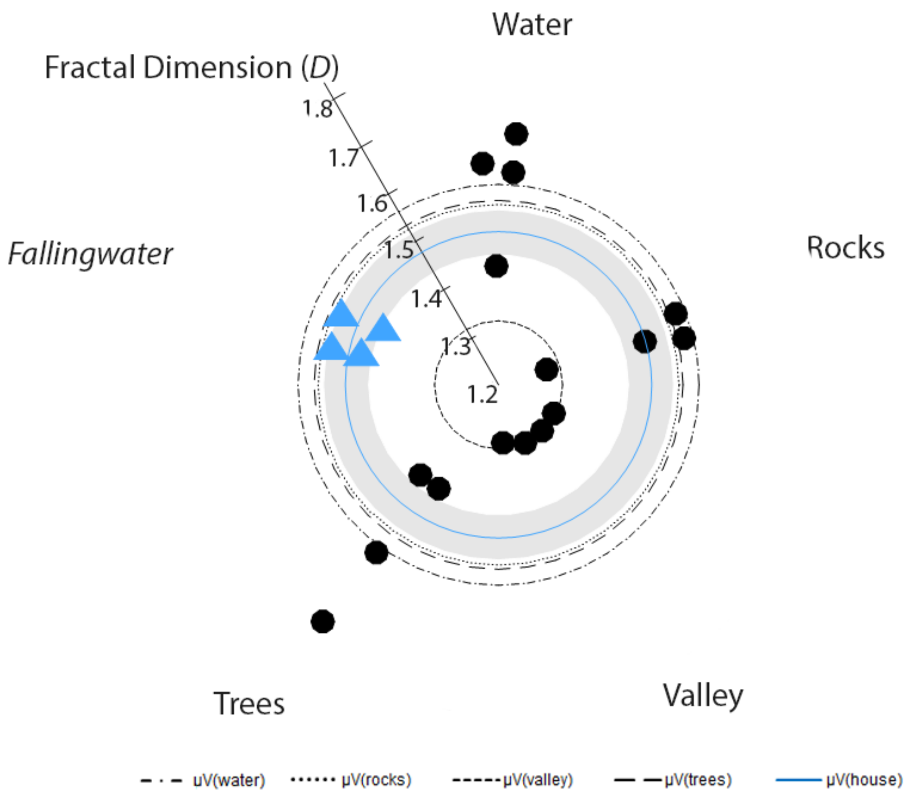
The views of the valley are the least complex of all the natural elements analysed, and rather than representing just one object such as a tree or a rock, these images are landscape views over a greater distribution of area. While all the results for the valley views are relatively similar, the highest is the view from the north ($D_{V1}$ = 1.3200), which looks across the Bear Run gully to the road used to approach the house. The least complex view is the view from the west ($D_{V4}$ = 1.3109), which is taken from a viewpoint down in the stream which is constrained by the steep gully sides.

Of the plan views, the nautical chart of the water has the highest fractal dimension ($D_P$ = 1.4671) and the rocks have the lowest level of complexity in plan ($D_P$ = 1.1630). The plan of the rocks which was analysed lacks detail and while it provides some qualitative information, as it is an aerial view many complex aspects of the outcrop, such as the cliff-line, are represented by a single line, and thus the image may not be fully representative of its character. Likewise, the tree plans which have a similar level of representational detail to the rocks, have only a slightly higher fractal dimension ($D_P$ = 1.1787); while the contour drawing used to measure the valley in plan has a higher level of complexity which is closer to those of the waterway ($D_P$ = 1.3378).

Excluding the plans from the mean results, the water set has the highest fractal dimension ($\mu_V$ = 1.5639), followed by the trees ($\mu_V$ = 1.5363) and then the rocks ($\mu_V$ = 1.5215); while the valley has a noticeably lower level of visual complexity ($\mu_V$ = 1.3165). The range of the results for the four views of the valley show the images to be visually indistinguishable ($R_{V\%}$ = 0.91) and the standard deviation, while only for a very small data sets, confirms this (*SD* = 0.0039). The range for the views of the rocks is similar ($R_{V\%}$ = 7.06, *SD* = 0.7614); in contrast, the views of the water ($R_{V\%}$ = 23.34, *SD* = 0.1005) and the trees ($R_{V\%}$ = 31.74, *SD* = 0.1508) are so different that they affectively unrelated. These last two ranges signal several challenges for interpreting the results. In essence, there is so much difference between these results that the mean is not necessarily useful for interpreting or comparing some of the data.

## 6 Discussion

For the individual views analysed, half of the results from the natural elements are higher than the perspective views of *Fallingwater* ($1.4354 < D_V < 1.5170$) and the remainder are lower (Fig. 3). There is only one exception; the image of one of the rocks ($D_{V3}$ = 1.4744) sits within the range of results for perspective views of *Fallingwater.* All the valley views and one representative from each of the other elements are less visually complex than *Fallingwater.* This confirms that generally, the results for natural elements are richer in detail than the perspective views of the house, and this can also be confirmed by the positioning of the mean trendlines for the natural elements compared to that of the house. Fig. 3 visualises the differences or similarities between perspective views of *Fallingwater* (results within the grey band) and the views of the natural elements with a lower value (within the central circle) and the natural elements with greater visual complexity (outer band of results).



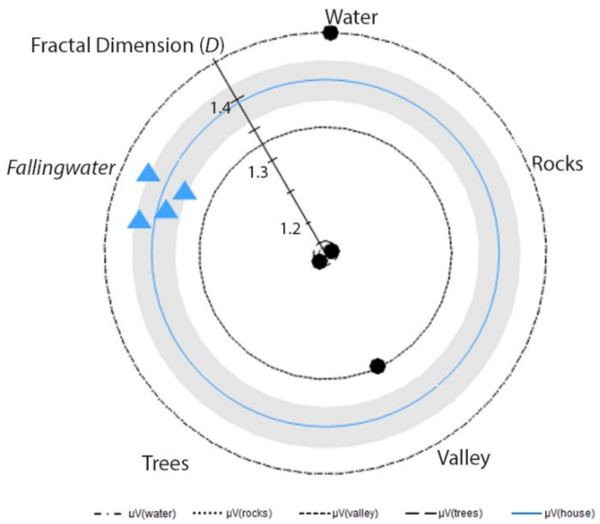




*Figure 3 Graphic spread of results data – Views(above) and Plans (below)*

The plan results, which do not have the same volume of data, show a different pattern to the views. None of the plans of natural element fall within the range of the house plans ($1.3540 < D_P < 1.4291$). Only one of the natural element plans has a higher result; the nautical chart Wright used to represent the waterway of Bear Run in plan. The contour plan for the valley ($D_P = 1.3378$) is not much lower than the ground floor plan of the house ($D_{P0} = 1.3540$), however the other plans are all significantly lower. Fig. 3 visualizes the differences or similarities between the plans of *Fallingwater* (within the grey band) and the plans of the natural elements with a lower value (within the central circle) and the only natural element with greater visual complexity (outer band of results).

When interpreting the data, in terms of the premise being tested in this paper, the results for range may be most significant. If the range is very small, then the images are visually similar. If the range is large, then they are dissimilar. The range values for the results are set using *Fallingwater* as a target value, and the $R_{\%}$ values provided are the difference between the $\mu$ value for the natural element and the $\mu$ value for *Fallingwater* (Table 3), noting that for a few 'means', there is only one data point. Thus, the $R_{\mu}$ indicates the percentage by which the natural elements differ from *Fallingwater*, in view ($R_{\mu V\%}$) and in plan ($R_{\mu P\%}$). Using qualitative descriptors for range (Ostwald and Vaughan, 2016), two of the views and one of the plans of the natural elements could be considered to be 'very similar' to those of the house. These are the view sets of the rocks ($R_{\mu V\%}$= 4.30) and the trees ($R_{\mu V\%}$= 5.48), and the contour plan of the valley ($R_{\mu P\%}$ = 5.46). In both view ($R_{\mu V\%}$= 8.54) and plan ($R_{\mu P\%}$ = 7.47), the water can be considered broadly 'similar' to *Fallingwater*, which seems fitting considering the name of the house and the significance Wright accorded Bear Run in the design. The complexity of the valley views are only 'comparable' to the house views ($R_{\mu V\%}$= 16.20); however the plans of the rocks and trees cannot justifiably be compared to the plans of *Fallingwater*, as they are visually 'unrelated' ($R_{\mu P\%}$ = 22.94, $R_{\mu P\%}$ = 21.37). However, as very few of the mean results are for data sets with low standard deviations, such an interpretation would be simplistic. Indeed, of the 15 natural analogue views, only one is within the same range as the views of *Fallingwater* and of the four natural plan views, none are within the same range as the plans of *Fallingwater*.

*Table 3 Comparison of mean results*

| | | $\mu_V$ | $\mu_P$ | $R_{\mu V\%}$ | $R_{\mu P\%}$ |
|---|---|---|---|---|---|
| Natural element | *Water* | 1.5639 | 1.4671 | 8.54 | 7.47 |
| | *Rocks* | 1.5215 | 1.1630 | 4.30 | 22.94 |
| | *Valley* | 1.3165 | 1.3378 | 16.20 | 5.46 |
| | *Tree* | 1.5333 | 1.1787 | 5.48 | 21.37 |
| House | *Fallingwater* | 1.4785 | 1.3924 | 0.00 | 0.00 |

## 7 Conclusion

Within the limits of the method used, and the sources of data chosen, this paper demonstrates that the form of *Fallingwater* does not strongly reflect the form of its natural setting. Certainly, a difference between some elements of the building and of nature of 5.46% < $R$ < 22.94%, suggests that a few broad visual similarities ($R$ = 5.46%), but most others are completely 'unrelated' ($R$ = 22.94%). On balance, as many scholars are adamant that *Fallingwater* is an example of Wright's aim 'to achieve an indivisible bond' between architecture and landscape (De Long, 1996, p. 120), the proposal that this house is visually similar to its landscape could be considered disproved in this paper. The evidence broadly supports the argument that *Fallingwater* is dissimilar to its surroundings (Frampton, 1994; Smith, 2000).

Despite these findings, even using the best applications and frameworks available, rigorously comparing the visual appearance of architecture and nature is a challenge. Thus, while testing an argument about *Fallingwater* is the primary goal of the research, the paper is also the first to apply a detailed and consistent rationale in the selection process for identifying appropriate images to compare nature and architecture using fractal dimensions, and the first to test this more rigorous approach based on specific claims. Compared to previous work in this area, this paper uses more examples (of nature and architecture) leading to more data and the capacity to use some basic statistical approaches. However, despite the larger volume of data, and the more carefully chosen sets, a perfect result was never anticipated. Instead, the significance of this paper is at least partially its demonstration of the best method and set of measures possible at this time.

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