

# How Not To Be A Circle:



## Dimensionless Ratios as Shape Descriptors

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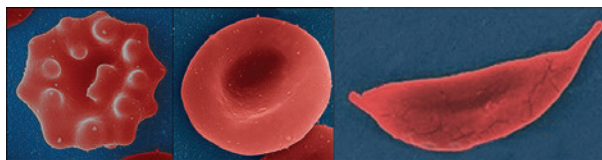
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**Ratios of size measurements that are formally dimensionless are provided by most image analysis systems as parameters intended to describe the shape of objects. The two most common are aspect ratio (which is measured in several ways) and formfactor (which also has other names). These are intended to provide complementary descriptions of deviations of the shape from a circle, one representing elongation and the other boundary irregularity. Measurement of the aspect ratio of a variety of shapes based on different definitions for the “length” and “breadth” values used to calculate the ratio, does not indicate that any of the various methods in common use offers a clear advantage in all cases. Formfactor describes only a narrow class of deviations from an ideal circular shape, and when applied to a variety of natural objects provides only weak separation. This paper compares the values obtained with these measurements, and shows that choosing a particular model or models to describe or compare shapes within a narrow range of objects can be useful, but requires careful consideration of what each calculation represents. None of the models consistently corresponds to the visual impression of the shape of objects.**

Shape is a basic characteristic of objects that humans rely upon for classification and recognition, and also use to correlate changes over time or due to environmental effects, processing variables, treatments, growth, etc. This is often important for microscope images, in fields such as materials science, archaeology, forensics, biology and medicine. But there are few descriptive words that uniquely define what shape means, and for most purposes a numerical representation is desired.

Measures of object shape include a broad range of techniques that require significant computation, such as Fourier and wavelet analysis, the medial axis transform, morphological set theory, and others (Neal & Russ, 2012; Ghosh & Deguschi, 2008; Costa & Cesar, 2009, Dryden & Mardia, 2016). These produce arrays of numbers that are often used with statistical programs, but the results may not reflect any physical or biological significance, and the numbers do not translate well into human visual experience for judging shape. However, practically every image analysis software program includes at least a few simple combinations of size measurements that are formally dimensionless, and so, within the limits imposed by image resolution, are related only to shape, without regard to size, position or orientation.

Dimensionless ratios have been used as shape descriptors in a wide range of microscope applications, such as recognition of various diseases in red blood cells (Figure 1). Malarial infection increases the length of the perimeter but does not alter the approximately equiaxed dimensions, while sickle cell anaemia is marked by an elongated shape with an increased aspect ratio. These changes are measured by the ratios introduced below, with values as listed in the figure.



	malaria	normal	anemia
L/Bmin	1.118	1.121	2.789
Cc/Ci	1.185	1.121	3.460
Rmom	1.047	1.124	2.890
FormF	0.761	0.909	0.436

Figure 1. Human red blood cells. From left to right: malarial infection, healthy, and anaemic, with a table of measured ratios defined in the following sections.

Many other objects have shapes that vary from circular by different amounts and in different ways, such as diatoms and pollen. Dimensionless ratios have been used for: forensic identification of animal and human hair as well as other fibres including man-made materials; distinction of various similar fish species based on otolith shape; correlation of seed shape with depth distribution in soils; forensic identification of particles; classification of bacteria and virus particles; and detection of cancerous cells and tumours. In some cases the studies have relied upon extensive statistical analysis, occasionally with the addition of Fourier shape coefficients, size information, or colour values.

Shape changes may also be indicative of materials processing. Steel used in automobile bodies, appliances, and other products is made into thin sheets by cold rolling to reduce the thickness. The process also strengthens the steel and causes the shapes of the grains to become squashed in the thickness direction and elongated in the rolling direction. Figure 2 shows examples of the microstructure after various percentages of thickness reduction. Measuring the elongation by the aspect ratio shows correlation with the amount of thickness reduction. Similar elongation can be seen in the cells of many plant stems.

Of all the dimensionless ratios, aspect ratio seems to be one of the simplest and most readily understandable, ideally representing the elongation or stretching of a shape. It is generally described as “length divided by breadth” and the length and breadth values are often conveniently represented as an ellipse, which is usually scaled to have the same area as the original shape. In some cases the inverse (breadth/length) is reported as the aspect ratio, and sometimes the eccentricity of the ellipse

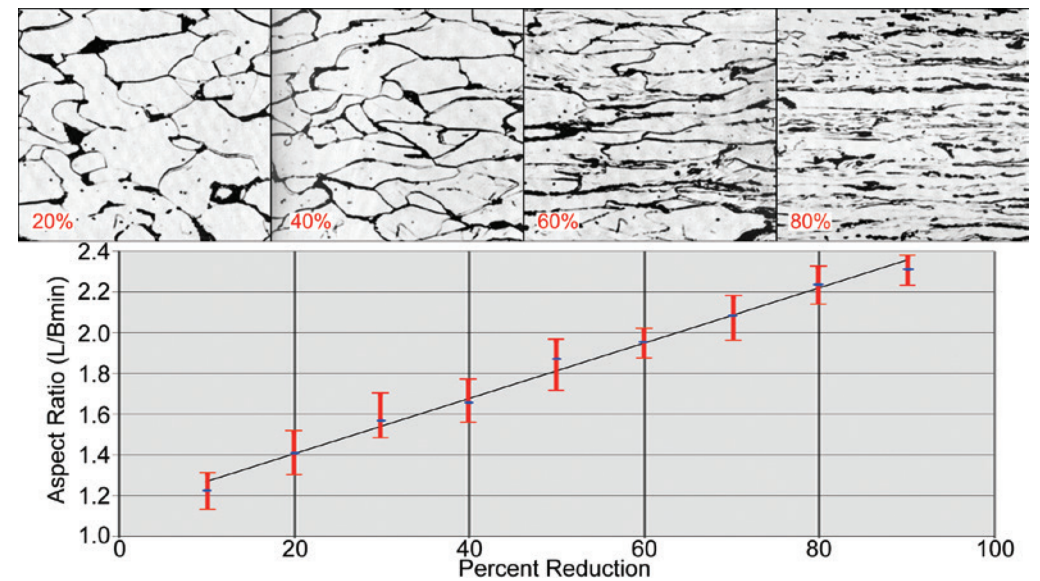


Figure 2. Microstructure of steel after various amounts of thickness reduction by cold rolling, and the correlation of grain aspect ratio with percent thickness reduction.

is used instead, but this can be calculated from the ellipse axes. Many different programs may be used to perform the measurements and calculate the values, but not all of the data reported as “aspect ratio” are based on the same measurements. This paper uses familiar objects, both microscopic and macroscopic, to make the meanings and choices for the various algorithms, and their consequence, as clear as possible.

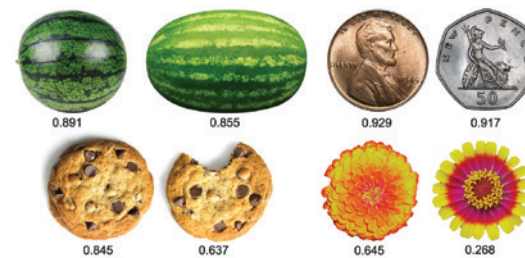


Figure 3. Departures from circularity (elongation, polygonization, indentation, irregular edges), each labelled with the measured formfactor value.

The difficulties arise because there are several different definitions and implementations of procedures for making the length and breadth measurements, which lead to quite different representations of the shape. It is only when

the original shape is an actual ellipse that they produce the same result. Several of the methods for determining an aspect ratio are illustrated in the examples that follow. These are based on two-dimensional binarized images, but all of these relationships extend directly and naturally to three-dimensional shapes as well.

The second most common dimensionless ratio that many programs provide combines area and the square of perimeter, usually as  $[4\pi \cdot \text{Area} / \text{Perimeter}^2]$ , but sometimes as the inverse and sometimes without the  $4\pi$ . This is called by a wide variety of names such as Roundness, Circularity, Formfactor, etc., (some of which may also be used for other dimensionless ratios). “Formfactor” is the oldest name, first used in the 1960’s and 1970’s by Quantimet<sup>®</sup>, one of the first (analogue) image analysis computers, and is the name used here. The intent is to quantify irregularity of the object boundary as it varies from being a smooth circle, since for a perfect circle the ratio calculates 1.0 exactly. Unfortunately, there are many ways to be “not like a circle” as illustrated in Figure 3. The formfactor values show significant changes only for shapes with an irregular edge that greatly increases the perimeter without

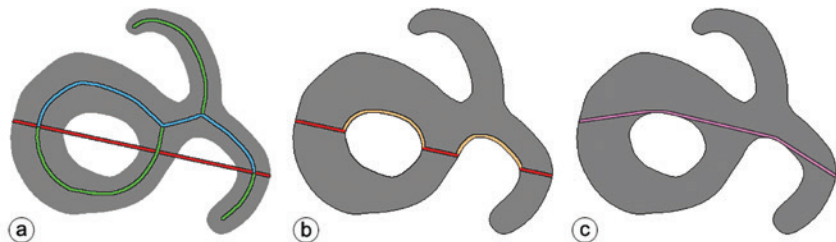


Figure 4. Measuring the length along a path that stays within the object boundaries: a) summing skeleton branch lengths (blue) that give the shortest total. The red line marks the straight line length measurement between the locations farthest apart; b) using the object boundary (orange) to connect segments of the shortest straight line (red); c) the actual shortest path (magenta) between the most distant points within the feature.

affecting the area. There is a similar relationship in 3D combining surface area and volume; measuring the surface area in 3D by placing triangular facets onto cubic voxels is significantly more difficult than determining perimeter in a 2D image.

One reason for the interest in having descriptions of the departure from “being like a circle” is because a commonly used measure of object size is the equivalent circular diameter (or, in 3D the equivalent spherical diameter). That is the diameter that encloses the same area (or volume) as that of the recorded image. Combining that with a meaningful measure of the departure from circularity is an attractive idea for obtaining a fuller and more useful characterisation of the object. How well the simplest dimensionless ratios such as aspect ratio and formfactor fill that need is the subject of this paper.

### Defining Length and Breadth

Length is usually defined as the maximum straight line distance between any two points in the feature, which is the maximum projected dimension or calliper dimension of the shape, also called the maximum Feret’s diameter. Ideally this is understood as the maximum projected value obtained as the viewpoint is rotated through all angles. However, many programs sample the projected length in finite steps, counting on the fact that the cosine function has values very close to 1.0 for relatively small angles.

For example, if the differences between the maximum and minimum rotated coordinates of points on the periphery are compared every 10 degrees to determine the maximum projected length, the worst case error occurs when the actual maximum lies 5 degrees away from the measured

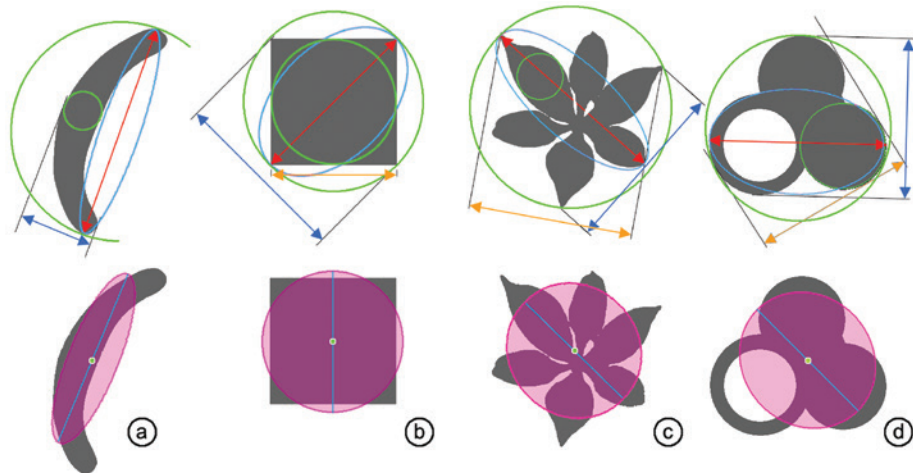


Figure 5. Comparison of the measurements of four shapes based on the inscribed and circumscribed circle diameters (green), the minimum projected calliper width (orange), the projected calliper width (blue) perpendicular to the maximum calliper dimension (red), the ellipse defined by the measured length and the total area (cyan), and the ellipse based on the moment axes (magenta).

value, but amounts to only 0.4%, or 1 pixel out of 250. Since repeated images of the same object falling in slightly different positions on the pixel grid can be expected to have slight variations in dimension, this error may be ignored. If the orientation of the length dimension is used to measure object orientation, this method causes the value to be quantized in steps.

If instead of the straight line distance between the two farthest points, the length is defined as the distance that stays within the bounds of the object, the calculation is more complicated and few programs report a value. One method uses the medial axis (or skeleton) as shown in Figure 4a; the sum of lengths of branches giving the smallest total may be adjusted with the values of the medial axis at the end points to correct for the local width. The difficulty of measuring the length of the irregular skeleton line is the same as that described below for measuring perimeter. Another method uses the shortest portion of the object boundary to connect points where the shortest straight line path intersects it (Figure 4b). Both methods overestimate the actual shortest distance (Figure 4c), whose determination is computationally intensive.

If breadth is defined based on the same procedure as the maximum projected length, as the minimum value of the projected dimension in a series of directions, a more serious difficulty arises. For a very long and thin shape, the measured minimum projected width is the product of the object length and the sine of the angle between the measured orientation and the true minimum value, and may not depend on the actual minor dimension of the shape at all. Increasing the number of directions (reducing the maximum possible error in angle) does not necessarily reduce this error. Finding the actual minimum projected dimension is computationally expensive, and for shapes that are even slightly “bent” (Figure 5a) may have little meaning, if the interest is in determining the minimum calliper distance that the shape would be able to pass through (as, for instance, if particles are sorted with a shaker sieve).

There are various “solutions” to this problem. One is to use as the minimum dimension the diameter of the largest inscribed circle in the shape. This is robust, and solves the problem for the shape in Figure 5a by defining a minimum calliper dimension that would correspond to a sieve size. This minimum dimension is often combined with the diameter of the smallest circumscribed circle (which is usually greater than the length defined as the maximum distance between two points). The result may be called the aspect ratio or the diameter ratio, and it, too, can define an ellipse fitted to the shape.

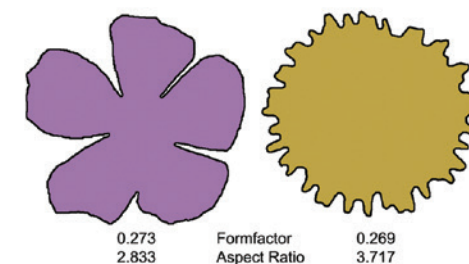


Figure 6. Measurements of a violet and a dandelion as described in the text.

Another approach is to measure the projected or calliper dimension of the shape in the direction perpendicular to the length axis. Depending on the actual shape, this may significantly overestimate the actual minor dimension. For example, the minimum projected dimension of a square is the length of a side (Figure 5b), but the projected dimension perpendicular to the length is the opposite diagonal. The aspect ratio values produced by the different methods are 1.414 or 1.0, respectively. Using the direction perpendicular to the length to measure the width is sometimes described as fitting a minimum bounding box around the shape (alternatively, the idea of the minimum bounding box may be defined based on minimising the area of the box, which does not necessarily produce the same result).

Another method calculates a minor axis for the shape based on an ellipse with major axis equal to the length value and having the same area as the actual shape. This works perfectly if the shape

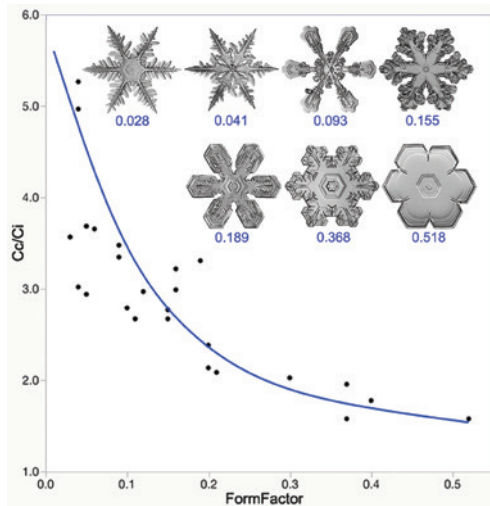


Figure 7. Variation in snowflake shapes from dendritic to platelike (images courtesy Dr. Kenneth Libbrecht) labelled with the formfactor, with a plot of formfactor and the ratio of circumscribed to inscribed circle diameter.

is actually an ellipse, of course, but in most cases it produces a much smaller value for the breadth and a much larger aspect ratio. Figure 5c shows an example, comparing the aspect ratio from this definition to those based on inscribed and circumscribed diameters and minimum projected calliper dimension.

All of these approaches except for the maximum inscribed circle deal with points on the exterior boundary of the shape and ignore the presence of any interior holes, and so correspond to the “filled”

shape that includes any interior holes. This can cause significant bias and misrepresentation in some cases (Figure 5d).

A different approach to aspect ratio uses the moments of the shape. The preceding methods (as well as those based on Fourier and wavelet analysis) deal with the boundary of the object. Determining the central moments about the x- and y-axes of the image is based on the distance of all pixels within the shape from axes through the centroid, calculated with a simple set of sums:

$$\mu_{pq} = \sum_i \sum_j (x_i - x_{cg})^p \cdot (y_j - y_{cg})^q \quad (1)$$

This approach deals automatically with internal holes, and is also less sensitive to boundary pixels that may be imperfectly delineated in the thresholding procedure. A full set of moments completely represents the shape, and can be used to reconstruct it exactly. But only the first few of these are needed to define an equivalent ellipse. The orientation, and the aspect ratio based on these length and breadth values, are well behaved for a wide range of shapes. The elliptical representation of the shape using this aspect ratio and orientation, and matching the actual area of the shape, is shown in the bottom row of Figure 5. Note the significant differences, including the orientation of the major ellipse axis.

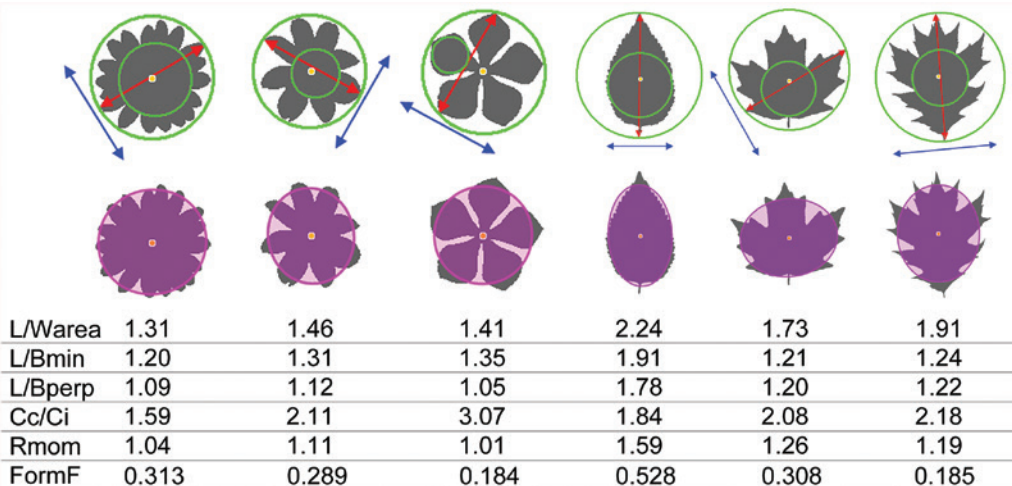


Figure 8. Several shapes, with the same color-coded measurements as in Figure 5, and the resulting measured values.

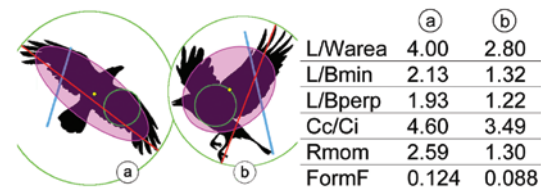


Figure 9. Silhouettes of a bird, with measurements.

There are several ways to combine the dimensions identified above to construct an aspect ratio, which are illustrated in the examples with numerical values in the following order (sadly, we were unable to invent short, unique descriptive names for each of these methods):

**L/Warea** - The length (maximum projected dimension) divided by the width of an ellipse with the length as the major axis and an area equal to the object.

**L/Bmin** - The length divided by the minimum projected dimension in any direction.

**L/Bperp** - The length divided by the projected dimension measured perpendicular to the length direction.

**Cc/Ci** - The ratio of diameters of the minimum circumscribed circle and the maximum inscribed circle.

**Rmom** - The aspect ratio calculated from the moments of the shape.

## Measuring Perimeter and Area

Figure 3 shows that the measured formfactor for a “perfectly” circular coin is less than 1.0. This arises because of the way pixels are used for the measurement of area and perimeter. Area is often a simple count of the number of pixels, converted to real units based on an entered calibration that corresponds to the pixel spacing. Another possibility is to form a polygon using the centres of the boundary pixels, which gives a smaller value.

Perimeter is most often calculated by forming a boundary connecting the centres of the boundary pixels. This chain code overestimates the length of lines and curves, increasing the perimeter and reducing the calculated formfactor, and also introduces directional bias in the measurements,

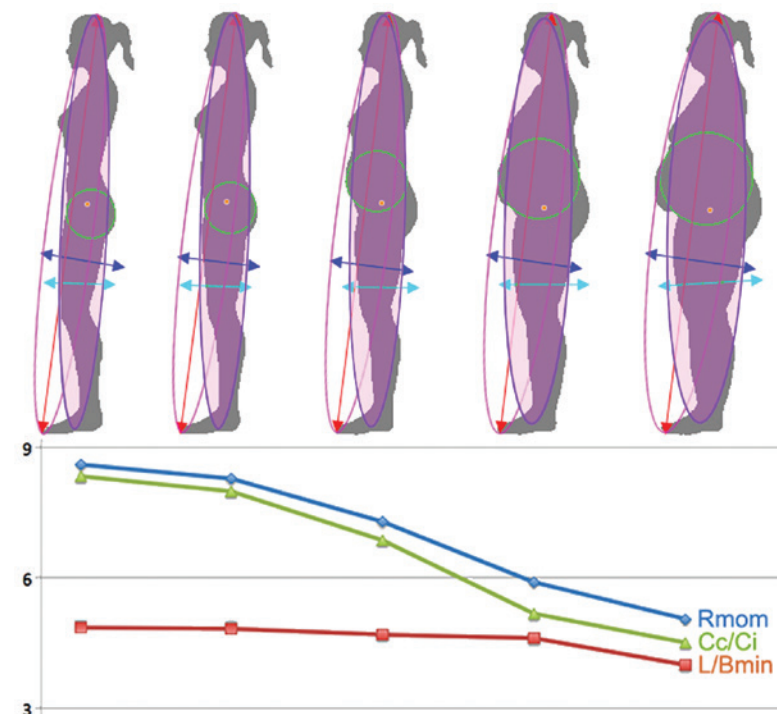


Figure 10. Measurement of figure profiles ranging from anorexic to obese.

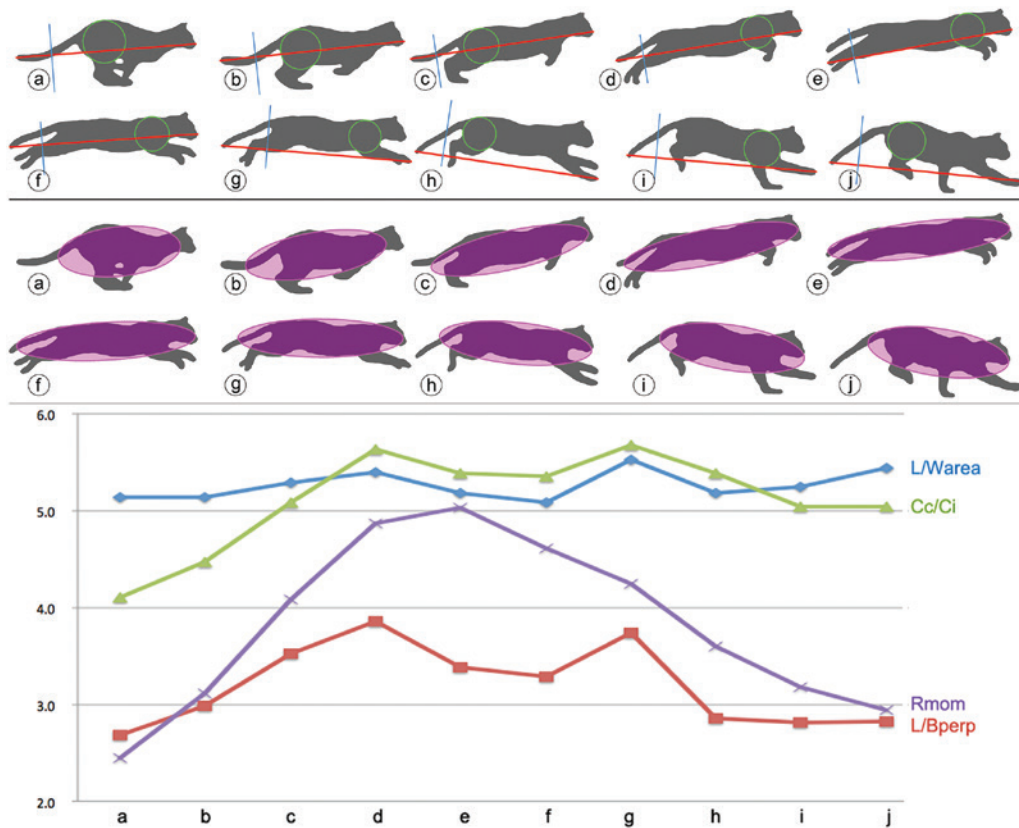


Figure 11. A sequence of ten images of a pouncing cat, with measurement lines and the resulting aspect ratios.

which causes the measured length of boundaries to vary depending on their accidental orientation on the pixel grid. Using either the centres or corners of the boundary pixels is biased; the inconsistency is easily demonstrated when measuring interior holes in a shape, since the dimensions of the hole based on the pixels that surround it is different than would be obtained if contrast were reversed and the hole treated as an object.

A further complication when perimeter is measured is that for many objects, increasing the magnification (reducing the relative size of the pixels to the overall dimension) reveals more irregularities in the boundary, increasing the perimeter. Only objects with ideally smooth boundaries, such as bubbles, are not affected by this phenomenon. However the area and perimeter are measured, the formfactor calculation would be expected to best characterise variations in shape that involve edge irregularities.

Figure 6 indicates that this is not always so. The images of a violet and a dandelion have practically identical formfactors, and in this case it is one of the aspect ratio definitions, the ratio of circumscribed to inscribed circle diameters, that provides a clear distinction.

### Examples

The endless variety of snowflake shapes, their beauty, and the physical basis for the shape variations, has captured the imagination of many. The basic hexagonal form arises from the underlying crystal structure of water. At a temperature of about  $-5^{\circ}\text{C}$ , ice crystals form as thin plates. Depending on the humidity, these grow with variations from solid hexagons to dendrites. Figure 7 shows some examples of the shapes, labelled with the formfactor. Since each snowflake experiences a different history of motion through the cloud and encounters

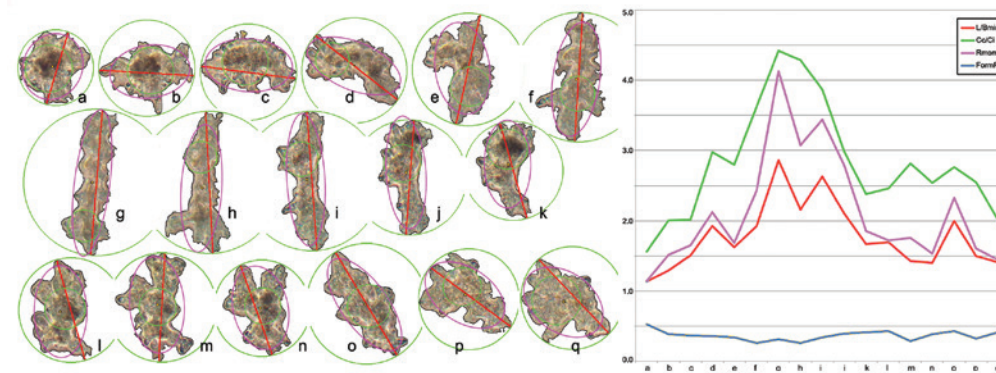


Figure 12. Sequential images of a moving amoeba (frames from a time-lapse video by Eduardo Ludwig), with superimposed measurements and graphs of results for the series.

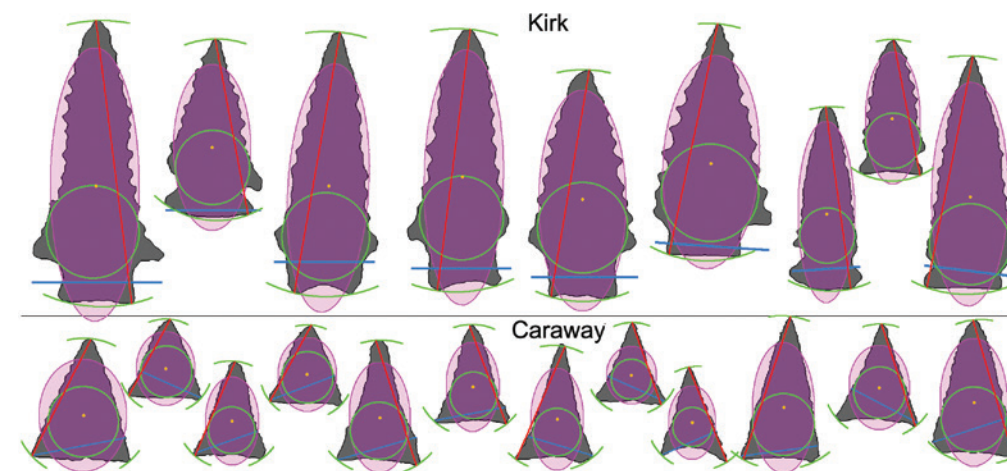


Figure 13. Examples of scanned silhouettes of archaic arrow points (images courtesy Dr. Billy Oliver, North Carolina State Archaeology Research Center).

different local conditions during the growth process, the flakes that develop vary widely in final shape. Because of the general hexagonal form, the shapes are all relatively equiaxed and it is the increase in perimeter and decrease in area that causes the drop in formfactor for dendritic flakes. But the other

significant measure is the ratio of circumscribed to inscribed diameter.

The shapes in Figure 8 are flowers with approximate radial symmetry and leaves with approximate bilateral symmetry. Figure 9 shows images of

	Kirk	-----	Caraway	-----
	Mean	%Std.Dev.	Mean	%Std.Dev.
L/Warea	3.019	13.6	2.075	16.8
L/Bmin	2.267	10.7	1.510	11.7
Cc/Ci	2.762	8.3	2.188	10.2
Rmom	2.744	19.5	1.610	25.1
FormF	0.451	7.31	0.530	11.78

Table 1. Statistical summaries for the arrow point measurements.

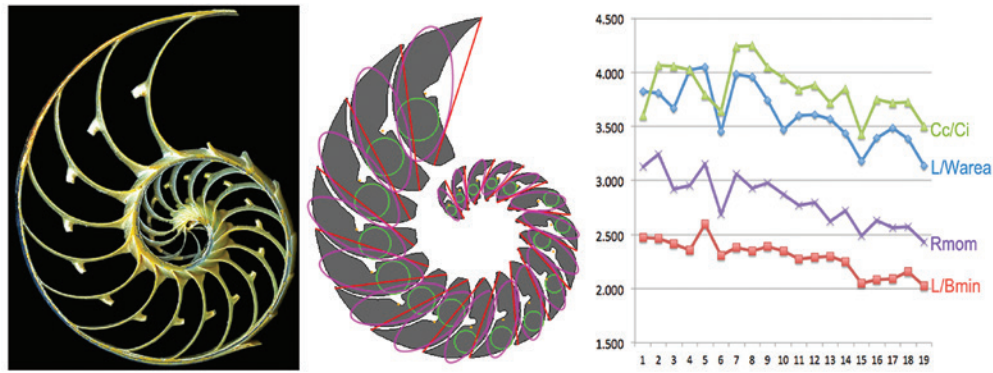


Figure 14. Measurements of aspect ratio for a chambered nautilus, showing a gradual trend toward less elongated chambers.

the same bird, in different poses. Examination of the data is discouraging in terms of reaching any general conclusion. As expected, the numerical values provided by L/Warea (using a width calculated from an ellipse with the measured area and length) are always greater than L/Bmin and L/Bperp. The value of L/Bmin, using a breadth given by the minimum projected dimension, is never less than L/Bperp, which uses the projected breadth measured perpendicular to the length direction, but the magnitudes of the differences vary widely. The different measures of shape offer no clear advantage to any one method, and show no evident correlations between the different values. Nor do the data consistently suggest agreement with the visual appearance of the shapes.

Since one of the purposes of measuring shape is to provide a means of correlating changes

with variations that may arise from differences in environmental effects such as mechanical wear or nutrition, or genetic causes, or processing history, it is also interesting to consider whether one or another of the aspect ratio measurements is most suitable. Figure 10 shows a series of human profiles ranging from anorexic to grossly obese, with several different measures of aspect ratio. As shown in the graph, length divided by minimum projected breadth [L/Bmin] does very poorly, but either the diameter ratio [C/Ci] or the ratio of moments [Rmom] can be used to track the differences.

As another example, Figure 11 shows a series of images of a pouncing cat, thresholded from one of Eadward Muybridge's 100 year old series of still images recording motion. As indicated in the graph, the ratios of length to width based on area, the ratio of length to the perpendicular breadth, and

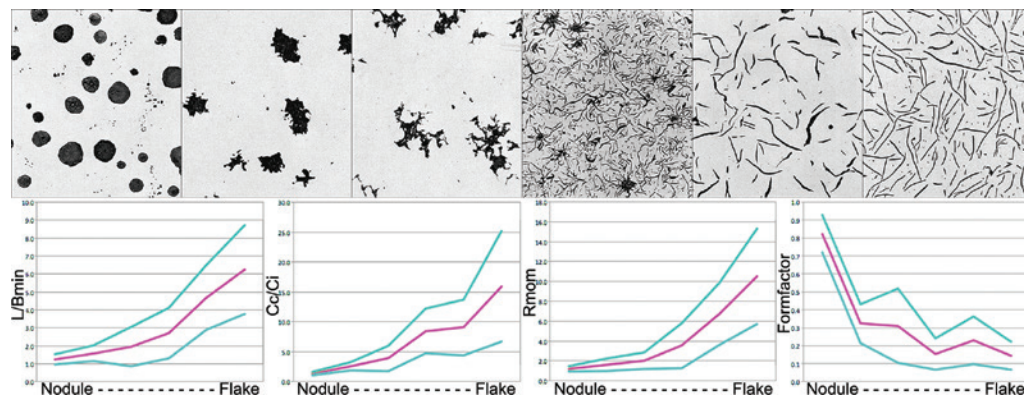


Figure 15. Micrographs of a series of cast irons, varying from nodular to flake morphology, with graphs for the various measured shape ratios. The blue lines show the range of measured values and the red line indicates the mean.

the ratio of circumscribed to inscribed diameter, vary erratically and do not correspond to the smooth motion and changes in shape of the cat. As shown in the figure, this is because the length measurement shifts back and forth between the nose or forepaw and the tail or hind foot, while the breadth sometimes corresponds to the back and sometimes to the head position. The inscribed circle shifts back and forth between the hindquarters and the shoulder. Consequently, the ratios that involve these measures exhibit erratic values. The moment ellipse, on the other hand, tracks the change in the cat's position smoothly and also corresponds to the overall angle of the cat's body.

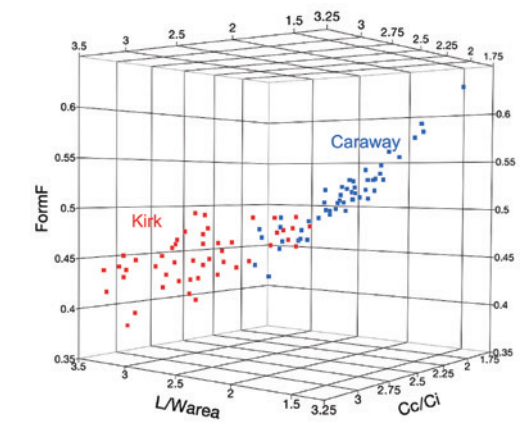


Figure 16. Measured aspect ratio and formfactor values for the arrow points.

Compared to the leaping cat, other progressive shape changes can be less regular. Figure 12 shows time-lapse images of an amoeba. The changes from one frame to the next are individually not great, but the overall alterations in orientation, size, and shape as the amoeba moves are substantial. As shown in the graphs, the ratio of circumscribed to inscribed diameter tracks the changes quite well. Formfactor is not a useful descriptor for the series.

Although Rmom and C/Ci data provide good representations for the pouncing cat and amoeba, they are not always the best choice. Figure 13 compares examples of more than 100 images of arrow points. The two styles shown date from

very different periods: the Kirk points from the Archaic before 6000 BC, and the Caraway from the Woodland period after 1000 AD. Variations within each style reflect differences between individuals, material characteristics, and random variables during manufacture, but each overall style is consistent and is used for identification and dating of sites and strata. The statistics in Table I show that the L/Bmin ratios are consistent within each group and provide better shape differentiation for these objects.

For shapes such as the points, which are approximately symmetrical but not elliptical, the use of aspect ratio seems reasonable. But even for shapes that are not symmetrical, using an elliptical shape as a model for elongation can be effective. Figure 14 shows a section through a chambered nautilus. It is often stated that the logarithmic spiral of growth produces self-similar shapes that simply increase in size. In this case, all of the various measures of aspect ratio are in agreement that the short term variations, probably due to environmental effects, are superimposed on a gradual trend toward less elongated shapes as the growth proceeds. The C/Ci ratio is the least useful in this case because the inscribed circle shifts position within the chambers.

The graphite in different grades of cast iron varies in shape from nodular, nearly spherical particles in a ductile metal to thin flakes in a stronger, more brittle material. As shown in Figure 15, there are a series of intermediate shapes, which can be measured using the various ratios. The general trend in all of the graphs is as expected, with increasing aspect ratios and decreasing formfactors with the variation from nodular to flake morphology. The spread of data for the various measurements emphasises the variation present in each specimen.

### Complementary Measures of Shape

Since aspect ratio and formfactor describe different ways for an object shape to vary from being circular, it is reasonable to ask if their combination can produce better results for classification. Applying

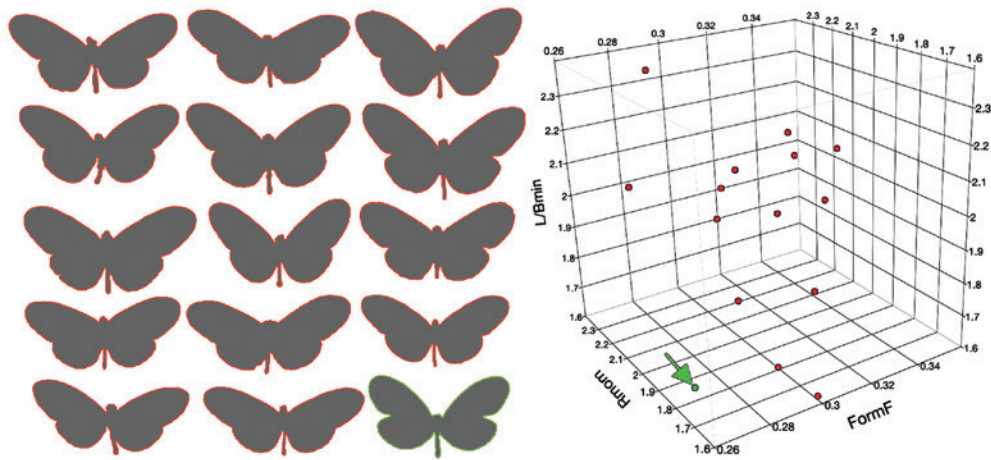


Figure 17. Silhouettes of butterflies (red outlines indicate *H. Melpomene*, green indicates *H. erato*, from E. Keogh (2007) Tutorial #7, Proceedings of the 13th ACM International Conference on Knowledge Discovery and Data Mining, with a scatterplot of measured aspect ratio and formfactor data.

linear discriminant analysis to the various measures of aspect ratio and the measured formfactor for all of the arrow points shown above selects L/Warea, Cc/Ci and formfactor as the most significant parameters for discrimination, and using a linear combination of the three variables is able to correctly identify 90% of the individual points. Figure 16 shows a scatterplot of the data.

Figure 17 shows a different situation. Fourteen of the butterfly silhouettes are specimens of *Heliconius erato* (red passion flower); the fifteenth, marked in

green, is *Heliconius melpomene* (postman). Based on a combination of aspect ratio and formfactor, can the single specimen be distinguished from the other population? The scatterplot suggests that it is possible. Nonparametric statistical tests (used because of the small number of data points) indicate a probability greater than 95%.

It is also interesting to compare the measurement of shape using dimensionless ratios to the visual impression of shape. In the 1940's and 50's, before the era of computer imaging and measurement, shape

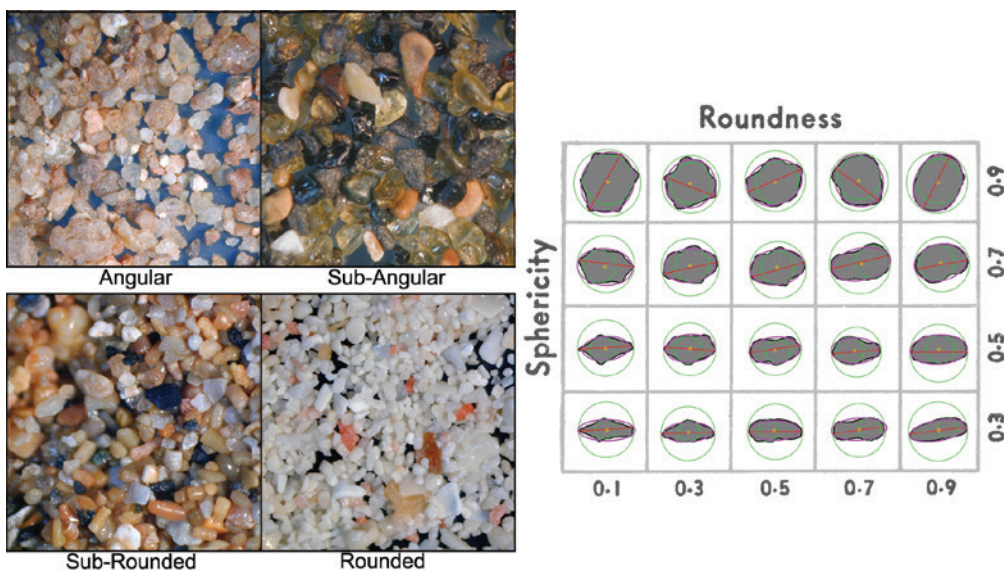


Figure 18. Examples of sand grains labelled according to visual shape, and a chart for visual comparison.

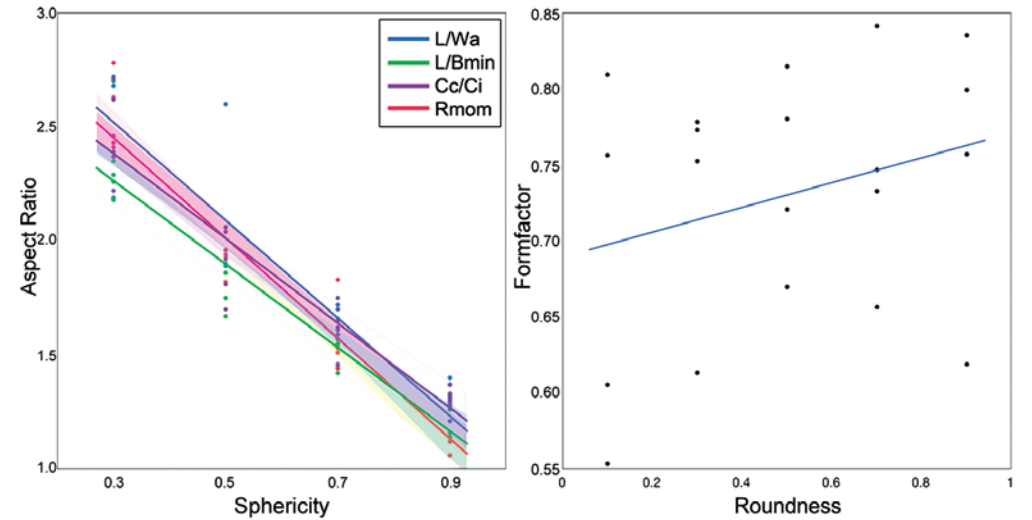


Figure 19. Correlation of aspect ratio measurements in the silhouettes in Figure 18 with the sphericity values, and poor agreement of the formfactor measurements with the roundness.

was evaluated visually by comparison to example images. This was especially applied to particulates such as sand grains. Sand is defined by a size range of particles (0.2-2.0 mm) and encompasses a wide variety of minerals. Because of the processes of erosion (by wind, water, and rubbing against other sand particles) the shapes of the particles vary.

A handy pocket guide to the visual classification of sand grains by shape was prepared and distributed by the Sigma Gamma Epsilon fraternity at Kent State University. As shown in Figure 18, it includes samples of grains described as angular, sub-angular, sub-rounded, and rounded, with a chart that attempts to visually define two shape variables, named "sphericity" and "roundness." These parameters were judged important to the packing density, permeability, and angle of repose of sediments, for example. The *sphericity* value is related to elongation of the shape, and *roundness* to the extent and sharpness of protrusions. It must be emphasised that these are visually determined, not measured.

The silhouettes were measured, and as shown by the graphs in Figure 19, all of the aspect ratio measures (L/Warea, L/Bmin, Cc/Ci, and Rmom) correlate well with the *sphericity* values, although the spread in the measured values is substantial. The *roundness* value is not related to any of the dimensionless shape

values. As shown in the graph, the formfactor, which has the highest correlation coefficient, is not useful for this purpose. Whatever visual cues are present in the silhouettes are not something that these measurements on the digitised images are able to represent.

## Conclusions

The aspect ratio ideally describes the elongation of an object, while the formfactor describes the irregularity of the boundary. But both of them are also affected by other characteristics of shape, and are not unique parameters that are always effective for identification, classification, correlation, or other purposes. Any of the various methods of defining and measuring "aspect ratio" and "formfactor" for an arbitrary shape may be useful in a particular instance for comparing or characterising a group of similar or related objects, but it is of the utmost importance that the user determine what measurement(s) are actually being performed in the software, and verify that the resulting values represent the important characteristic of shape that is of interest. Any of these measures may give misleading impressions of shape differences when used to compare objects that are different in overall form.

## References

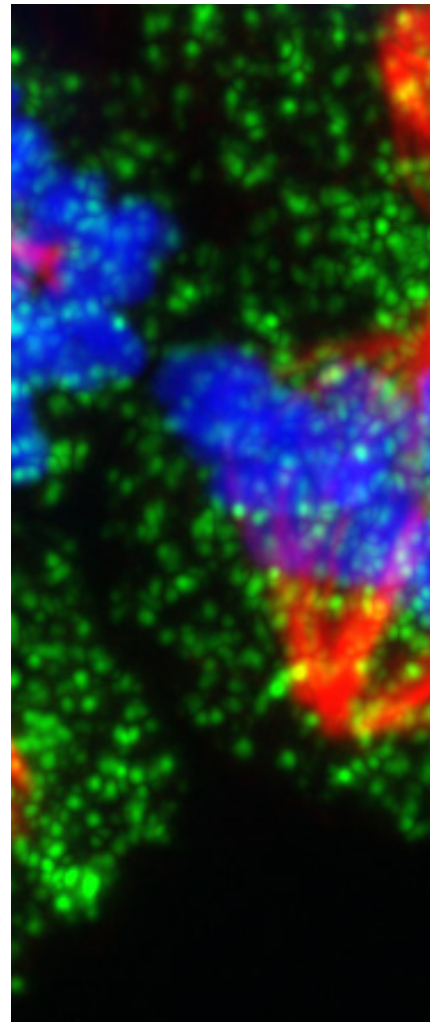
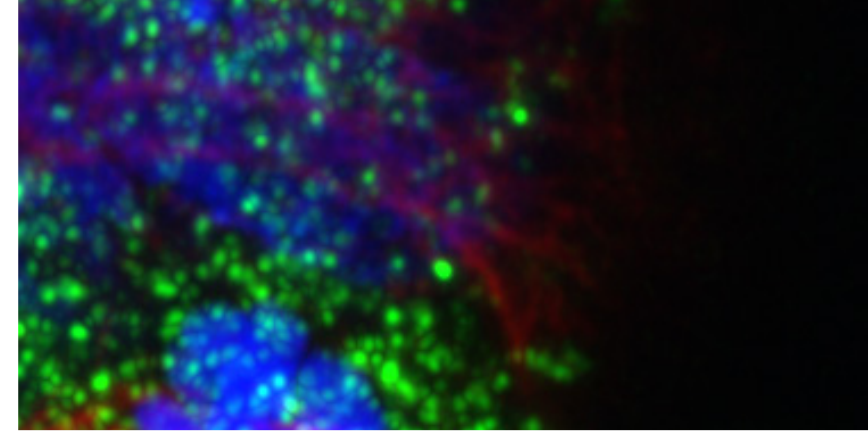
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We hope you will join us building a stronger European microscopy community, as we attempt to shed some light on what imaging can do...and perhaps drink a pint of Guinness!

**Abstract submission is now open at [www.elmi2018.eu](http://www.elmi2018.eu)**



**John Russ** is Emeritus Professor in the Department of Materials Science and Engineering, North Carolina State University.

In his fifty-year career as scientist and educator, Dr. Russ has used image processing and analysis as a principal tool for understanding and characterising the structure and function of materials. Images from a wide variety of devices – including light and electron microscopes, x-ray and neutron tomography, and more – require computer processing and measurement to extract the important data. Much of his research work has been concerned with the microstructure and surface topography of metals and ceramics. Familiarity with the algorithms and instruments led to Dr. Russ' expertise being extended to a much broader range of images, from astronomy, biomedical research, archaeology, food science and forensics. He has received the Ernst Abbe and August Köhler awards for contributions to the field of image processing and analysis.



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