Scale: A Fundamental Dimension in Spatial Representation

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ABSTRACT Scale is one of the most important but unsolved issues in various scientific disciplines, including spatial information science. In this paper, it has been argued that scale is one of the dimensions in spatial representation along with space and time. The theoretical background for such a transformation is outlined and mathematical means reviewed. Although the story in this paper is not perfect, it is hope that this paper will attract further contributions from other researchers because scale is a major unsolved issue in geographical information related sciences.
KEYWORDS Scale, scale dimension, transformation, natural Principle, resolution.

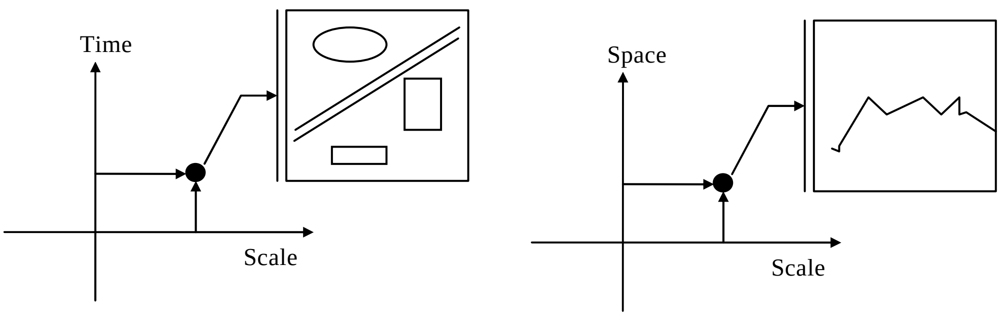
1. Introduction

"Scale is a confusing concept, often misunderstood, and meaning different things depending the context and disciplinary perspective" (Quattrochi and Goodchild, 1997, p395).

In cartography, maps are produced at certain scales, e.g. 1:10,000 and 1:100,000. For a given ground area, the map space is larger at a larger scale. For example, given a ground area of 10km x 10km, at 1:10,000 scale, the map space is 1m x 1m. However, at 1:100,000, the map space becomes 0.1m x 0.1m. It is intuitive that not the same level of details can be represented when the map scale is smaller. It means that the representation of the features in same area will be different when the map scale is different. The issue arising is "how to derive small scale maps from large scale maps" through some operations such as simplification and selective omission. This issue is called "map generalisation".

In geography, there is a similar issue. Normally, geographical data are sampled in small enumeration units. And in some applications, these data need to be aggregated to a larger enumeration unit. However, the statistical results will be different when the analysis is carried out based on different size of enumeration units (i.e. different scale). Therefore, there is an issue of "how to aggregate data from small enumeration units to larger units for processing". This issue is called "modifiable areal unit" issue (Openshaw, 1994) although some researchers have reservation on this issue (Tobler, 1989).

Indeed, there is a similar issue in all geographical information related sciences, such as geomorphology (de Boer, 1992), oceanography (Stommel, 1963), soil science (Hillel and Elrick, 1990), biology (Haury et al, 1977), biophysics (Friedl, 1997), social sciences (Dovers, 1994), hydrology (Blöschl and Sivapalan, 1995), environmental sciences (Bian, 1997), etc.
In Euclidean geometry, there is also a scale concept. An object may be reduced or enlarged in size. There is then a change of scale.



(a) A map is a record of reality at a given time and a given

(b) A chart of time series is a record of reality at a given space and a given

Figure 1 Representation of spatial and temporal variations

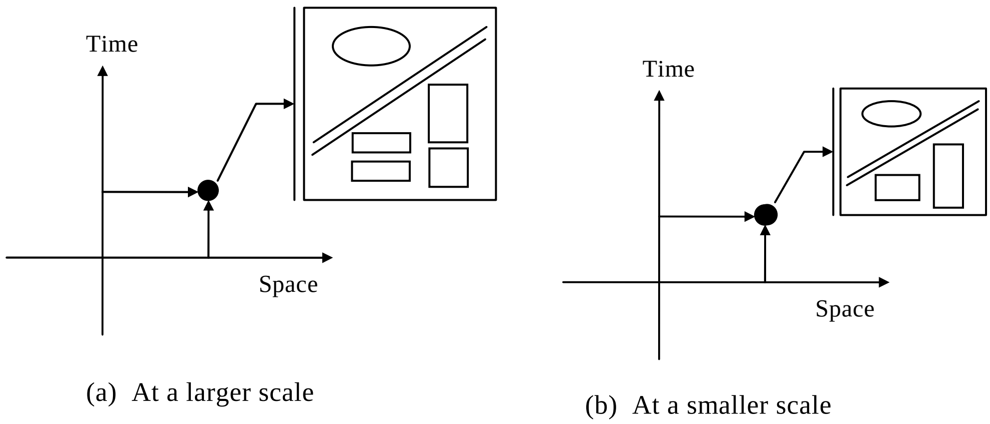


Figure 2 Representation of scale variations

One may have noticed that the term 'scale' used in Euclidean geometry has meanings different from those implied in geo-sciences. Indeed, scale is a term which is not well defined. “Of all words that have some degree of specialised scientific meaning, ‘scale’ is one of the most ambiguous and overloaded” (Goodchild and Quattrochi, 1997). This paper aims to clarify the cloud and argue that scale is one of the three fundamental dimensions in spatial representation, along with time and space.

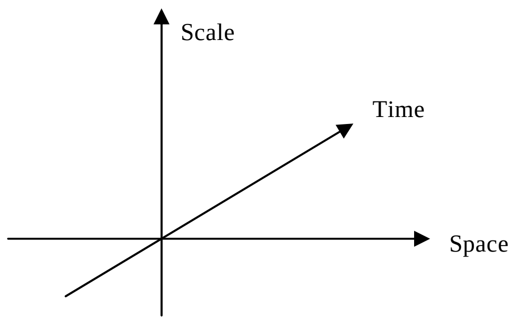


Figure 3 The time-scale-space systems

2. Scale As a Dimension in Time-Scale-Space Systems

Considering the current development in multi-dimensional data handling, space and times are the two “domains of interest”. A spatial representation could be a record in time-scale systems (Li, 1994). For example, a map is a record of spatial variations recorded at a given time and presented at a given scale (see Figure 1a). A time series is a representation of temporal variations in space-scale systems (see Figure 1b).

Indeed, it is also possible to represent scale variations at a given space and time. Figure 2 illustrates such an example.

Therefore, it becomes obvious that space, time and scale are the three independent parameters for the description of phenomena related to geo-sciences. These three parameters form Time-scale-space systems. In this system, time, scale and space are the three axes and thus three dimensions (Figure 3).

3. Transformation in Scale Dimension Versus Scale in Euclidean Geometry

One may ask "what do you mean by "trans-formation in scale dimension?" and "Is this simply another jargon or is there any different meaning from the scale in Euclidean geom-etry?" This section is devoted to answer these questions.

It is well-known that in Euclidean geometry, the size of any object can be enlarged or reduced by a factor. This factor is called 'scale'. The process of enlargement or reduction is called 'scalling'. In this process, the complexity of the object is not changed with a change in size. Figure 4 illustrates an example of such a change in the X-Y plane.

However, geo-phenomena are not that simple. In almost every case, the complexity of spatial objects one observed varies with scale. When a person is nearer an object, s/he can see more details. When one gets further away from the object, less detailed information can be seen but the main characteristics of the object can be better observed, thus better overview being gained. Li and Openshaw (1993) have used the Earth being viewed from various distances as an example. If one views the terrain surface from an satellite, then terrain surfaces becomes very smooth. These phenomena can easily checked by forming a stereo-model from a pair of satellite images such as SPOT images or Spacelab Metric

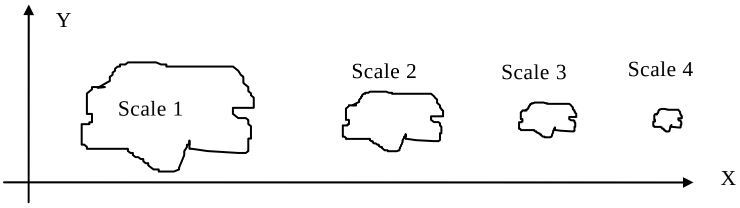


Figure 4 Simple scale reduction in space in Euclidean geometry: complexity not reduced

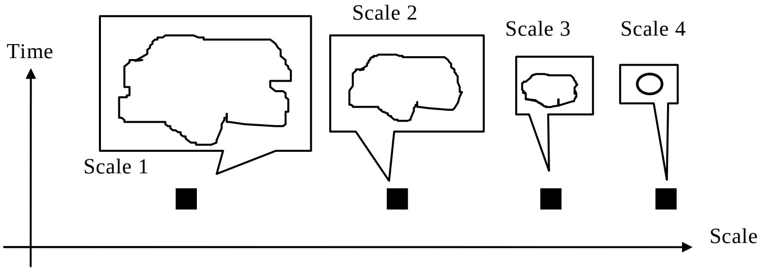
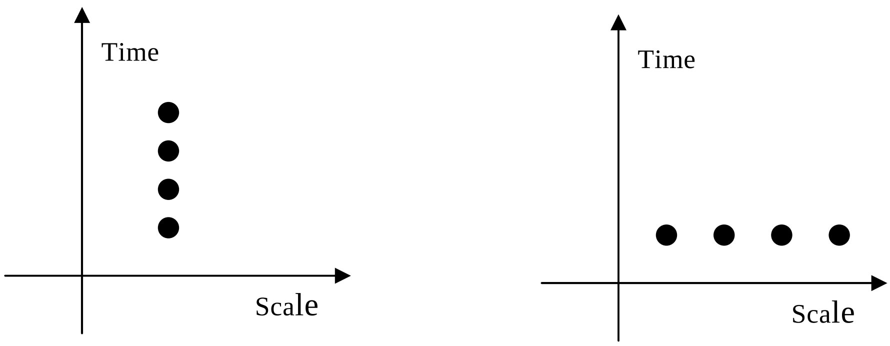


Figure 5 Transformation in scale dimension: complexity changed:



(a) In temporal dimension (b) In scale dimension

Figure 6 Transformations in scale and temporal dimension

Camera photography. The model of such a stereo-model is at a very small scale. When one views the terrain surface from an airplane, small details disappear and the main characteristics of the terrain variations become very clear. It is a commonplace to photogrammetrists that the stereo-models formed from high altitude photography are more generalised than those formed from low altitude photography. These are just some out of many practical examples illustrating the transformation in scale dimension. In such a transformation, the complexity of spatial objects has been changed with a change of scale (Li, 1996). Figure 5 illustrates the transformation in scale dimension.

The difference between the transformations in Figures 4 and 5 is very clear. These are graphic illustrations only. The intrinsic difference in theory is as follows:

The reduction of the size of the representation of objects without change of its complexity can be understood with following line of thought: When the size of the representation of the object is changed, the basic resolution of the observational instrument is also changed by the same magnification.

The transformation in multi-scale representation can be understood with the following line of thought: The change of complexity of spatial representation is achieved by changing the relationship between the size of the object and the basic resolution of the observation instrument. There are ways to achieve this result. The first is to change the size of the representation of the object but, at the same time, to retain the basic resolution of the observational instrument. The second way is (a) to retain the size of the representation of the objects unchanged but to change the basic resolution of the observation instrument, then (b) to change the size of observed representation of objects by simple reduction in Euclidean space.

In fact, the transformation in scale dimension is performed when time is fixed while transformation in time dimension is performed when scale is fixed (Figure 6). The transformation in time dimension is called temporal modelling and lies outside the scope of this paper.

4. A natural Principle for Transformation in Scale Dimension:

Now the question arising is "how to perform transformation in scale direction?" Indeed, this follows a natural principle.

In the case of human observation, it is due to the limitation of eyes' resolution. That is, all information within the limitation of human resolution disappears. In the example given in the previous section, the terrain surface will appear at different level of abstraction if it is viewed from different heights. This is also due to the limitation of human eyes' resolution. When the viewpoint is higher, the ground area corresponding the human eyes' resolution becomes larger, thus the ground surface appears to be more abstract. In the case of stereo-models formed from images, it is due to the resolution of images. That is, all information within the image resolution (e.g. 10m per pixel in the case of SPOT images) disappears. These examples underline a universal principle, a natural principle as called by Li and Openshaw (1993), which states as follows:

"for a given scale of interest, all details about the spatial variations of geographic objects beyond certain limitation are unable to be presented and can thus be neglected".

It follows, therefore, that a simple corollary to this process can be used as a basis for the transformations in scale dimension. The corollary can be stated as follows:

"By using a criterion similar to the limitation of human eyes' resolution, and, neglecting all the information about the spatial variation of spatial objects beyond this limitation, some zooming effects can be achieved".

Fig.7 illustrates how it works. This principle describes the effect of zooming when a photograph is taken. This zooing effect is referred to as the transformation in scale dimension in the previous section. Indeed, based on this principle, some transformation models have already been developed (Li and Openshaw, 1992; Li and Su, 1995; Su and Li, 1995, Su *et al*., 1997).

5. Mathematical Means for Transformations in Scale Dimension

To characterise a dimension, some measures should be designed. For example, in space dimension, mm, cm, m, km etc. have been in use. In time, second, minute and hours are in use. In scale dimension, the useful measure is the so-called 'resolution". For example, Figure 7 can be considered as the result of repres-entation at different resolutions.

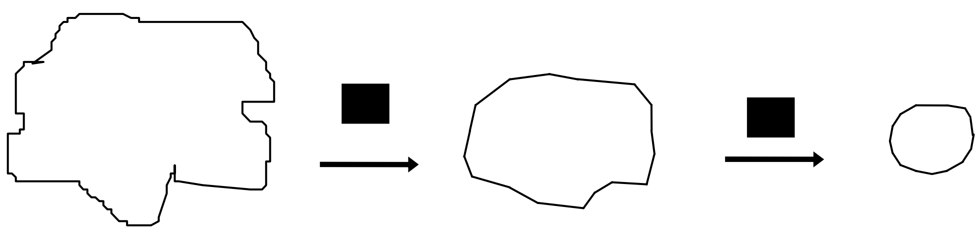
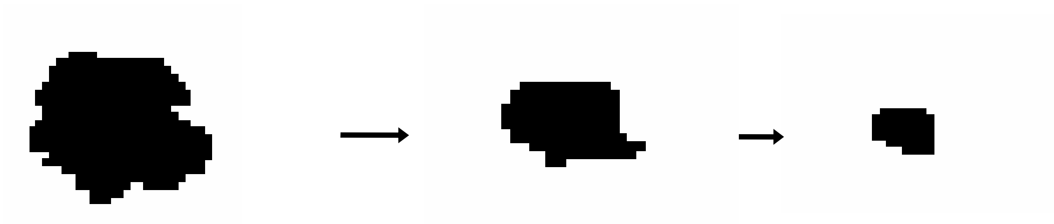


Figure 7 By neglecting the detailed spatial variations within the black square, the shape of the polygon is simplified.



(a) Original image (b) Shape simplified (c) Further simplified

Fig.8 Shape simplified by morphological operators

Indeed, all of our perceptions are scale-dependent. It has been discovered long time ago that different length values will be obtained if rulers with different resolutions are used to measure a coastal line (Mandelbrot, 1967). The concept 'closeness' is also related to scale (resolution). At macro scale, people use "light year" as the basic resolution and, as a result, a distance of a few thousand kilometres can be considered to be extremely small. For example, the diameter of the Earth and other planets are considered to be zero in the Gravitation Law of Newton. On the other hand, at micro scale, a distance of a few micro metres can be considered to be very far apart.

It might be difficult to accept by many resea-rchers, but it is a fact that the spatial relations between objects are also scale-dependent. The topological relations, which would be of interest at micro scale are the molecular structure. These topological relations are not of interest to most geo-scientists. Indeed, such topological relations can be and should be totally neglected to most of geo-scientists. On the other extreme, at macro scale, the topological relations of consideration would be the structure of the solar system and beyond. At this scale, the Earth is viewed as a point and all the topological relations between features on the Earth can be and should be totally neglected. Even within the range of scales familiar to us, topological relations between fea-tures vary greatly with scale. For example, on a map at 1:1,000 scale (i.e. high degree of detail), almost every building and street are represe-nted and therefore, topological relationships between buildings and streets are of importance at this particular scale. On the other hand, on a map at 1:100,000 scale (higher degree of abstrac-tion), buildings need to be grouped together and individual streets may disappear. In this case, the classes of features like streets and buildings disappear and are replaced by new classes such as blocks. Therefore, topological relations-hips between blocks are of importance at this particular scale and topological relationships between buildings and streets then can and should be neglected. If the map scale is even smaller (higher level of abstraction), them a town may become a point symbol, and thus all topological relations between morphological operatorsTo deal with the transformation in scale dimen-sion, some mathematical transformation models are essential, like the conformal, affine and other transformation models in space dimension. Li (1996) illustrates that the operators developed in mathematical morphology form a set of toolkit for the development of such models (Figure 8). Xia and Clarke (1997) sugg-est that fractal geometry could be a mathe-matical means for such purpose.

6. Concluding Remarks

In this paper, it has been argued that scale is one of the dimensions in spatial representation along with space and time. The theoretical background for such a transformation is outlined and mathematical means reviewed. Although the story in this paper is not perfect, it is hope that this paper will attract further contributions from other researchers because scale is a major unsolved issue in geographical information related sciences although some attempts have been made (e.g. Montello, 1993; Li, 1994b; Bruegger, 1995, Li, 1996; Quattrochi and Goodchild, 1997).

Although the author is the first one to address scale dimension systematically. The argument in this paper is backed by discovers by many others.

Quattrochi and Goodchild (1997) point out that "Scale is undoubtedly one of the most fundamental aspects of any research". Cola (1997) argues that scale is such a pervasive issue in analysis of spatial data as to require it to be the level of a basic dimension, along with space, time and theme. This view is similar to the view previously expressed by the author (Li, 1994b; Li, 1996, Li, 1998), but from different angles. Indeed, Quattrochi and Goodchild (1997) in the Epilogue of their book also re-irritated a similar view: "Scale is a fundamental and inescapable dimension of geographic data".

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