Geographic Information Technology Training Alliance (GITTA) presents:

Fundamental spatial concepts

Responsible persons: Helmut Flitter

Table Of Content

1. Fundamental spatial concepts

There are some fundamental concepts of geographic information science: scale, distance, topology…

1.1. The Scale

The term of scale has been popularized by cartography. It is a well-defined geometric conceptthat needs to be understood.
Estimated time: 20 minutes

1.1.1. Definition

Scale [1]
The definition of scale for graphic elements is the same for representations on the screen as well as for representations on paper documents. Depending on the purpose of modeling, the modeling of reality is more complex or more general. This fact influences the scale. Which objects should be represented? Which geometric primitive should be chosen for a specific representation: Points, lines, polygons? Which generalization factor should be chosen to design the contours? In the following, similar issues are discussed:

Only pictures can be viewed in this version! For Flash, animations, movies etc. see online version. Only screenshots of animations will be displayed. [link]

How to evaluate the scale?
The scale corresponds to the degree of resolution in which the phenomena or the environment are described. It's an inherent property of the observation. Elements with a different precision can coexist in a spatial database. For example, the georeferencing of water hydrants is very accurate (accuracy of cadastral maps, several centimeters), while forest boundaries are at a resolution of few meters.
In the context of GIS it is essential to distinguish between **modeling scale or observation scale** and **scale of cartographic representation**. The choice of a scale depends on the modeling purpose. The purpose determines the presence and richness of spatial features which are described as well as the amount of information which is referred to the objects. The scale of cartographic representation is dictated by the technical, graphical, physical (capacity of the visual system) and aesthetic constraints. In practice, there is a big interdependence between these two types of scale because the map is both, a source of information about spatial elements as well as a product provided by GIS. One centimeter on a map at a scale of 1:25'000 corresponds to 250m in reality, or to 1km on a map with the scale of 1:100'000. Have a look at the examples below, the national maps extracted from the Federal Geo-Information center.

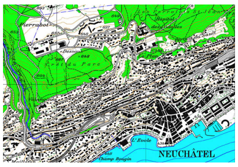
How to evaluate the scale?
A rule of thumb defines when an object becomes observable if represented on a cartographic document. It's reasonable to state that an area on the map, which is less than 1x1mm, can't be a zonal component. That's why the map scale is associated to the spatial resolution. It is recognized that a resolution of 10m for example corresponds to a spatial precision of the order of 1:10'000. This rule provides an order of magnitude

[1] The ratio between the measured distance on the map and the real distance.

which has to be exploited carefully. This rule is not valid for the display or the printout of digital images, as a fuzziness, unpleasant from a visual point of view, appears when the side of the pixel exceeds 0.3 to 0.4 mm.

Exercices

There are three maps with different spatial scales visible in the following.



National map 1:25'000 (source SwissTopo)

National map 1:100'000 (source SwissTopo)

National map 1:500'000 (source SwissTopo)

Note and comment on the differences between the maps. Which scale would you choose to represent your environment if you were:

- An eagle
- An ambler
- A farmer
- A mouse?

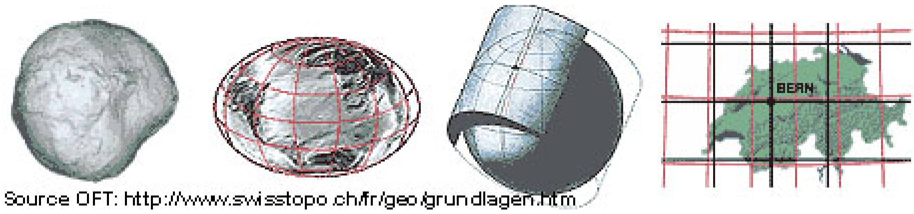
Comment on your choice.

Solution

The solutions will be discussed in the next lesson.

1.2. Georeferencing: Positioning and Projections

The location of objects in space describes both, its position in space as well as its relation to other objects. The location includes two concepts: The **position** and the **neighborhood**. In everyday life, the notion of neighborhood is often used to locate objects; for example, one would say that *the grocery store is located next to the church*. In this example, location involves the concept of neighborhood, the measuring of proximity in relation to a reference object whose position is perceived implicitly. Obviously, such a location does not fit to the description of a set of complex objects such as those described in GIS. In GIS the requirements are even higher as they were for conventional mapping. In this case, one talks about the positioning of objects on the terrestrial surface. The establishment of a reference system and the definition of a metric space to measure distances are necessary. The simplest and most frequently used system is the Euclidean metric. The space is assumed to be flat; the metric space is assumed to be constant, defined by a perpendicular axis system. The mapping systems based on this principle are adopted by GIS.

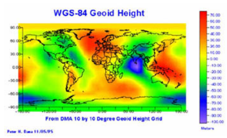


In addition you can consult the book "*Datums and Map Projections for remote sensing, GIS and surveying*" (Jonathan Iliffe 2000) .

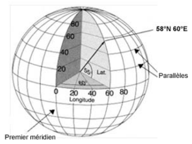
1.2.1. Georeferencing

The fundamental problem of the location of objects on the terrestrial surface is the curved shape of the relief and the earth being almost round. To display the information on a flat surface, the characteristics of geometric projection are used. Different projection methods have been developed.
By georeferencing objects, a referencing system is established for the positioning of the object on the terrestrial surface. If the reference system is called universal, it is the same for the entire planet, if it is called relative; it is related only to a region or a country. To simplify matters, the earth is preferably represented in a flat plain. To do so, different map projections have been developed in the way to establish a punctual relation between the terrestrial surface and its representation in the plain. There are some facts resumed in the following:

- The earth's surface is modeled geometrically by a gravitational equipotential surface, called geoid. The geoid is approximated by the ellipsoid of revolution, also known as spheroid. Note that the knowledge about the geoid has been improved with the advent of satellites. In order to ensure consistency, the national mapping systems base on ellipsoids which have been defined legally.



- In spherical coordinate systems, every point on the earth's surface is expressed by three parameters: Longitude (l), latitude (p) and distance from the center of the earth (r). If x and y are the coordinates, a projection is represented by the following function: $x = f(r, l, p)$ et $y = g(r, l, p)$



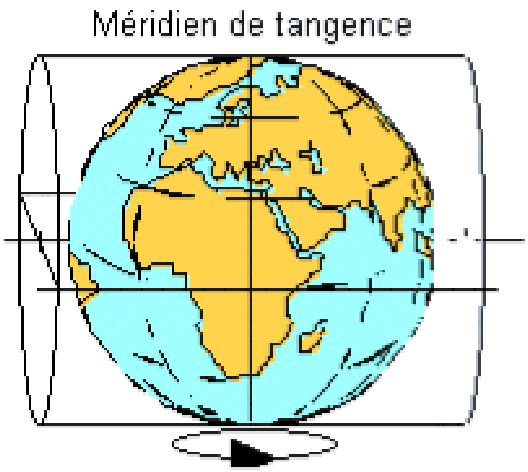
1.2.2. Map Projections

The laws of spherical and Euclidean geometry show that a map projection cannot be achieved without loss of information. There are two main types of map projection proposed by the geodetic sciences. Both of them conserve just one characteristic; the characteristic of orientation or the characteristic of the surface.

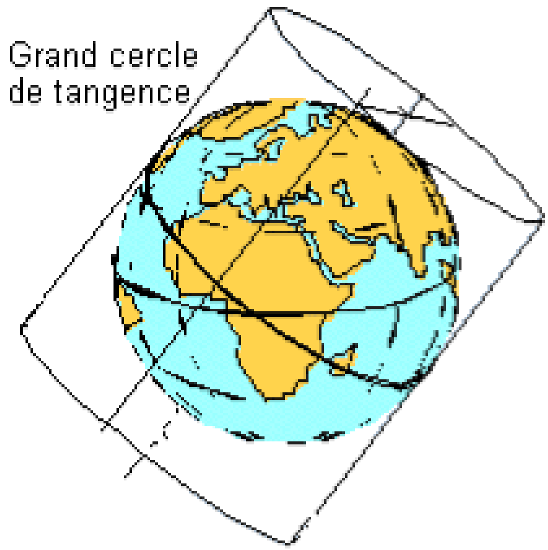
The *conformal* projection respects the relative directions; all shapes are preserved by respecting the angle between two directions. The *equal-area* projection represents accurately the area in all regions of the sphere. None of these projections conserves the real *distances*.

Topographic mapping is established generally according to the conformal projection. The projection mode is chosen in the way that on the local scale the distances are preserved within an acceptable error. There are a lot of different projections. The most common are the cylindrical projection and the conic projection. In this lesson, the basic elements are presented for students who have no training in this field. Generally, the objects of the ellipsoid are projected orthogonally, first on a reference sphere, then on a plain surface, the cylinder or the cone. The schemas of the different projections consider that the reference surface is already a sphere. A number of projection variants have been proposed. In the following, the main principles applied will be explained. The national georeferencing is generally expressed in meters, at an origin which avoids ambiguities between longitude and latitude.

Cylindrical projection



Projection sur un cylindre est-ouest

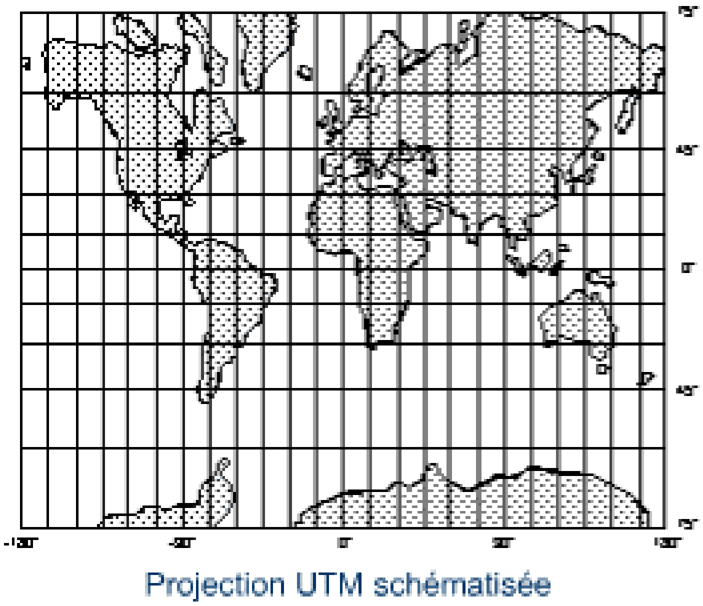


Projection sur un cylindre oblique

The figures above represent two possibilities of cylindrical projection. The cylinder on the left side represents the Transverse Mercator projection. Here, the line of tangency coincides with any chosen meridian. This projection is also called *UTM* [2] (Universal Transverse Mercator) projection. For each meridian, a new cylinder

[2] "Universal Transverse Mercator" (UTM); Gerhard Mercator, 1512-1594, Flemish mathematician.

is defined. In order to hold the linear deformation in every zone acceptable, narrow zones of 6° of longitude are chosen. This system divides the earth into 60 zones (cf. illustration below). The central meridian devides the zones 30 and 31 counted towards east. The illustration on the right shows the tangency coinciding with the great circle. This projection is called oblique Mercator projection.

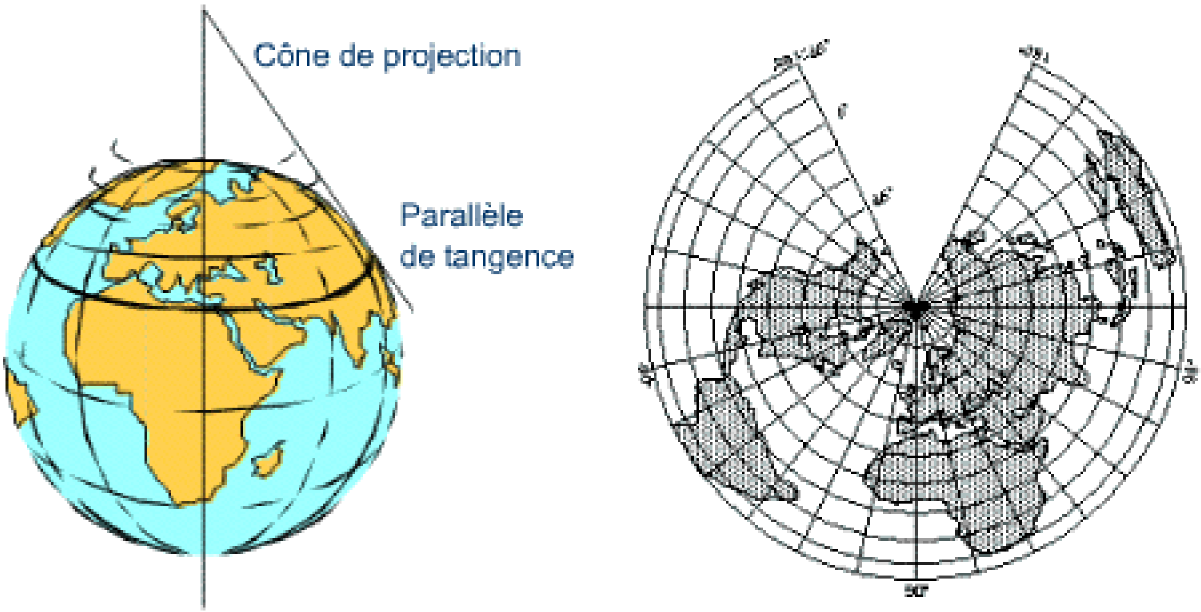


Projection UTM schématisée

Lambert conformal conic projection

The *Lambert* [3] conformal conic projection is a conic map projection. Here, a cone is superimposed over the sphere of the earth. The cone builds the tangency line that coincides with the parallels secant. This map projection is adopted by France. Four cones were necessary: three on the continent, one on the island of Corse. The meridian of origin, which is the meridian of the obervatory in Paris, became the y-axis.

[3] Jean-Henri Lambert, 1728-1777, French mathematician.



The figure shows a conic map projection. To learn more read (M. Brabant 1980)

Other georeferencing

Georeferencing is the basis for mapping. The georeference defines the spatial reference systems. There are also other reference systems known. They are combined with a spatial reference system mentioned above. Among them, the postal reference system, the regional reference system and the roads reference system should me mentioned. The continental European postal reference system is based on numbers which identifies the postal office responsible for the postal mail delivery. All the numbers are assigned to a geographic region, in order to optimize the distribution. Any person resident in the same region is assigned to the corresponding number. This kind of georeferencing plays a big role in "geomarketing". In market research, a correspondence between the social strata and the postal zone, in order to elaborate specific publicity, is established. The North American postal reference system is different. The space is devided into a regular grid (Theriault 1994). The road reference systems allow the unequivocal location of any events happening on the road network. Again, there are differences between the countries.

Only pictures can be viewed in this version! For Flash, animations, movies etc. see online version. Only screenshots of animations will be displayed. [link]

1.2.3. Positioning

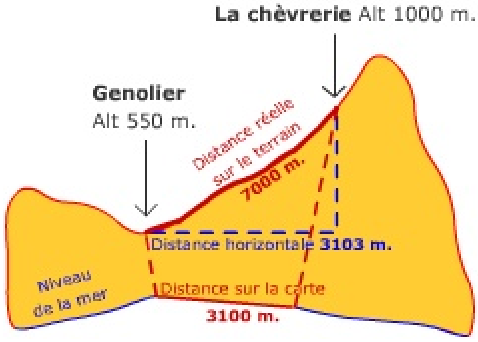
Positioning establishes, by means of coordinates, a point's most exact position possible. Positioning is realized by the application of methods developed in the field of geodesy. The accuracy of the positioning depends on the means invested. The accuracy can be very high, in the range of millimeters compared to a reference. Nowadays the accuracy is not limited by technical obstacles anymore. It's enough to pay the price! In the GIS context, the optimal accuracy referring to the scale of the phenomenon which is studied has to be obtained. The conventional positioning tools are surveying and photogrammetry. For a couple of years now, there is the satellite positioning system available, provided by the United States Department of Defense. The accuracy is 5 to 10m in direct mode using a low cost receiver, or in the range of centimeters using a more expensive differential receiver. Since 2008 there is the European system named Galileo.

1.3. Spatial Relations

Working on spatial entities involves the ability to locate and describe them individually as well as to comprehend them collectively by describing their relations in space. In order to model an area in GIS, it is essential to understand the terms of distance, topology and the influence of the dynamics of the environment.

1.3.1. Distance

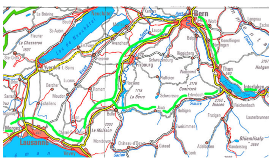
Spatial relations include very different situations. Two airports approached by the same airline are connected independently of their distance. In this case, the proximity is given by the flight time or the money spent for the ticket. Two mountain villages located in neighboring valleys separated by a mountain chain may have a common border but are remote in terms of traveling distance. The traveling time to get from one of the villages to the other could be greater than the flight time between the two airports mentioned above. Moreover, the trip depends on the traffic constraints as well.



In the illustration above there is a driving route drafted, containing some obstacles. The relief and the obstacles in the digital elevation model are taken into account by calculating the route.

1.3.2. Neighborhood

Spatial relations are constructed by asking quotidian questions. Does M. Dupont's parcel border on M. Durant's parcel? Does the river flow into the lake? Is M. Dubonnet's villa located near the railway line? Is there an air route connection between Paris and Montreal? How far is Lausanne from Paris? Which is the shortest path between two villages? Etc.

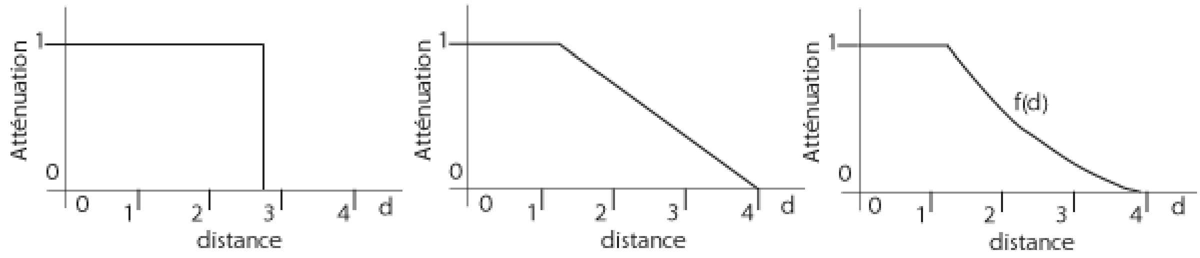


Which is the shortest way from Morges to Interlaken by car? Although the shortest way is via Jaun, it is faster to take the motorway via Bern. (source SwissTopo)

1.3.3. Spatial relations between thematic properties

Other situations depend on the relation between elements and the phenomena under consideration. The relation is not constant; it's a function of distance. This corresponds to phenomena which move in space having an origin and a destination and disperse progressively in the geographic space such as noise or a cloud of smoke.

In addition to the modeling of phenomena, GIS are applied to define the limits of proximity or neighborhood as well as to classify neighborhood. When does an object belong to another object's neighborhood? The answer to this question depends on the interpreter. The concept of neighborhood depends on the object of interest.



Les modèles d'atténuation

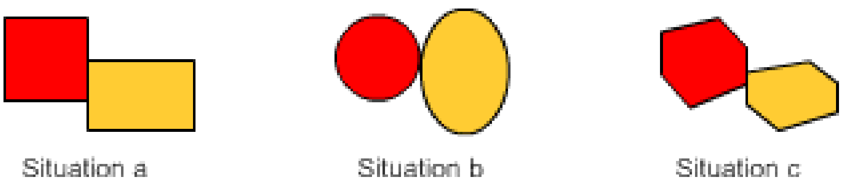
A spatial relation identifies all the properties between the spatial units. The spatial relation is always related to the concept of neighborhood or of liaison, which makes two phenomena depending on each other. Hence they are expressed by the geometry in the case of neighborhood or by liason functionally expressed in an attribute. The concept of neighborhood is discussed in the unit "Topological Relations". The concept of topology is discussed in the next unit.

1.4. Topology, fundamental concept

The geometric relations between objects can be described quantitatively by metrics: Distance (cf. unit 1.3 in this lesson), and qualitatively by topology. In this unit we will learn more about the concept of topology.
Time estimated: 20 minutes

1.4.1. Topological relations

The concept of topology is a common approach of human's mind to determine the reality. The visual perception is topological. When people look at landscapes, or when they consult a map or a plan, their immediate perception is global. Objects such as buildings, forests, agglomerations are perceived in the whole context. The term of neighborhood is implicit: *There is a river traversing the agglomeration, M. Dupond's parcel borders on M. Schmidt's parcel*.
That means, because of the perception of geographic space, topology is the collective of all the detected relations. This allows observers to locate objects in relation to other objects. Which object is next to another object? The "neighborhood" is therefore a spatial notion.
The concept of topology is a fundamental element in spatial analysis. Without it, it would be impossible to extract information about the neighborhood or about a river's drainage direction from the database. The concept of topology is known in several disciplines.
Mathematics gives a rigorous definition: "Propriétés des êtres géométriques subsistant après une déformation continue, et qui fait abstraction de la notion de distance". Sometimes it's also called: Geometry without metrics.
In other disciplines, the meaning of topology is broader. In social sciences, topology is an arrangement, a configuration of people and their relations.

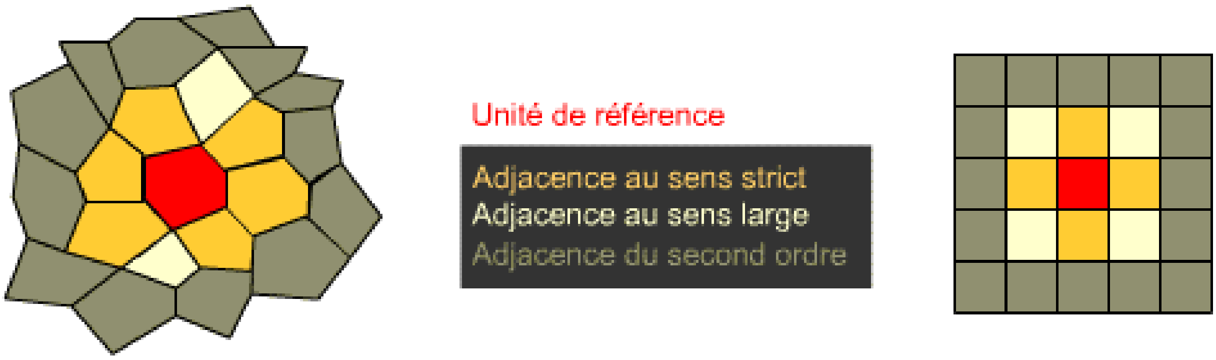


Les situations a, b et c de la figure sont équivalentes du point de vue topologique.

In GIS topology is used to get information about the proximity between the elements. The topological relations in this context are the adjacency, the connectivity, the inclusion and the intersection.

1.4.2. Adjacency

The concept of adjacency implies that the spatial elements share a side or a boundary. The adjacency is called strict if there is a boundary line in common; the adjacency is called broad if there is a vertex in common (cf. illustration above). It answers the following question: "What is next to what?"
However, the topology provides nuances in the concept of adjacency. It takes into account only the order in which the spatial elements are located away from the target device.
If the two objects are in contact, the adjacency is said to be of first order. If there is another object lying in between, it is called to be of second order etc. (cf. illustration below). The order of adjacency is of interest, for example in transportation to determine the number of transshipments required to move goods or people from one place to another.



1.4.3. Connectivity

Connectivity expresses the adjacency for linear networks. It links the constitutive segments of the network. When a distribution network of fluids (gas, water, electricity) or people is modeled, the connectivity is called to be oriented. In contrast, road networks are traversed in both directions, with exception of one-way streets. Connectivity is described by means of graphs and matrix, to indicate which elements are connected to each other. (Theriault 1994)

1.4.4. Inclusion

Inclusion occurs when a spatial element is completely located inside of another spatial element, such as an island in the ocean or departments and provinces within a country. Inclusion is a special case of adjacency.

1.4.5. Intersection

Intersection expresses the point of surface common to both entities.

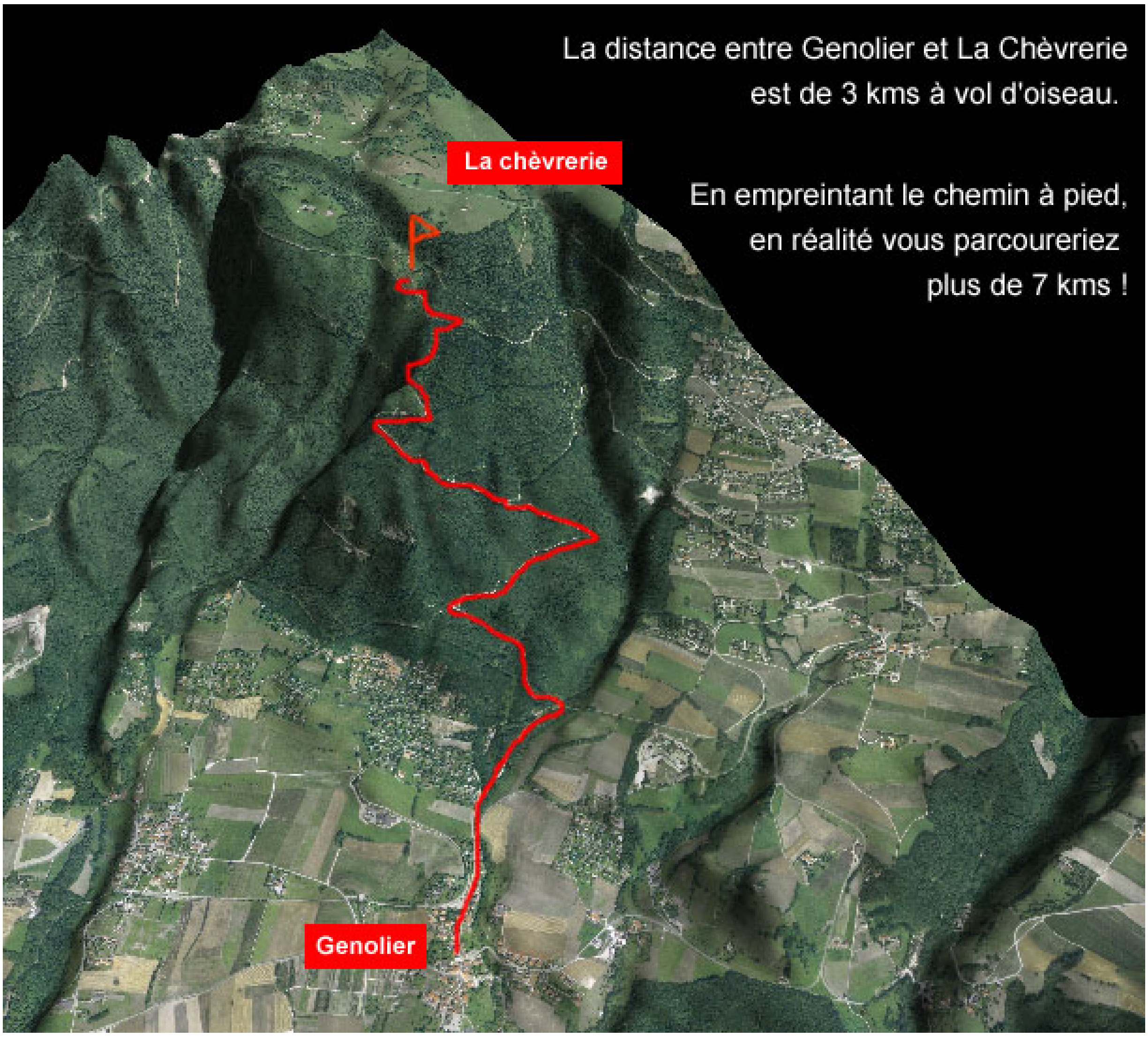
1.4.6. Multiple-choice test

Make the following multiple-choice test to test your knowledge of topological relations.

Only pictures can be viewed in this version! For Flash, animations, movies etc. see online version. Only screenshots of animations will be displayed. [link]

1.5. Spatial Distance and Properties of the Environment

The model of spatial reality contains more than just the description of phenomena and their characteristics. There are also elements which determine the spatial dynamic such as the processes of diffusion, of displacement or of propagation. We already found out that space can be considered in a simple way in the flat dimension, or taking other characteristics such as the altitude or the height of vegetation into account, or including directional forces. In this unit, the theme of movement is introduced.



1.5.1. Dynamics of space

Space can be modeled in different levels of complexity depending on the properties one would like to retain and depending on the predefined purpose. Let's look at the following example to illustrate the complexity: the ambler who moves in space. A plane and homogeneous surface is the simplest perception of space. The ambler can move in every direction with the same comfort. The distance to his destination would be a function of the Euclidian distance, measured from his starting point. His path would connect the starting point and the destination point by a straight line, giving the distance. In this case, the space is described as a **plane and**

isotropic surface. Space is supposed to be a homogeneous, isotropic surface and the distance is calculated based on the coordinates. But we have to be aware that such a surface without obstacles and without elements determining spatial dynamics does not exist in reality.

Imagine the ambler moving on a plane but heterogeneous surface with different land use types, vegetation covers, different geological formations etc. The observer will realize that the ambler's path is influenced by friction elements. The space is differentiated by specific properties, thus heterogeneous. This surface is still supposed to be **isotropic**. This means that the properties don't change with direction. But in this context, the Euclidean distance is not adequate anymore for the calculation of the distances. Other measurement units are necessary such as time or energy needed to go from one point to another based on the **concept of weighted distances**. To account for the surface's heterogeneity, the geometric aspects of the entities, which compose the space, have to be considered as well as their properties. Forests and marshland influence the movement differently.

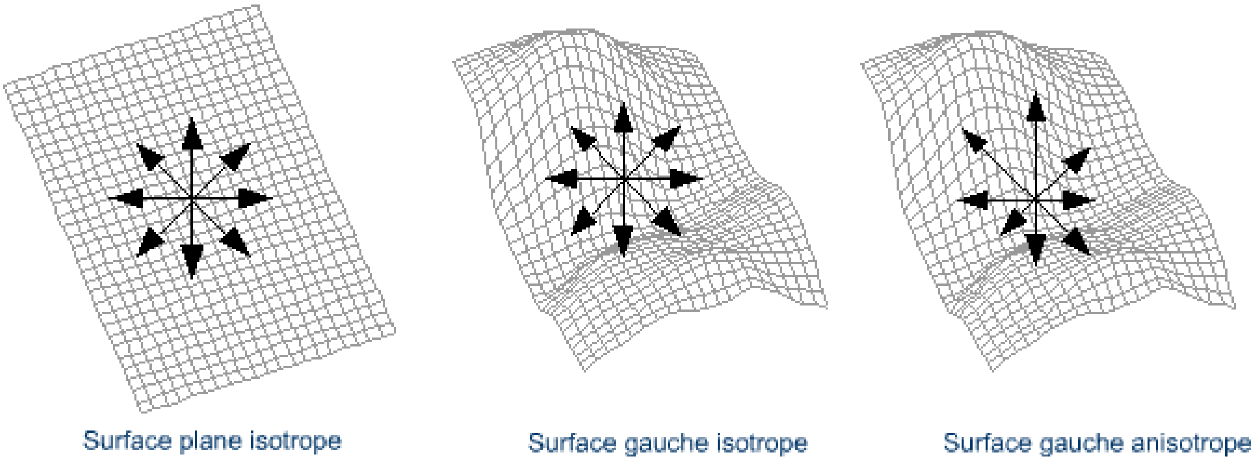
Consider the ambler moving in a rough terrain. In addition to the changing land cover types there is the topography as an element of friction taken into account. The topography acts as a gravitational force, depending on the slope, influencing the ambler's approach and certainly his path. The orientation of the movement is connected to the gravitational force. This space can be seen as **anisotropic surface**. It allows to include the area of influence of other phenomena which affect the ambler, e.g. wind and all other exterior forces influencing direction or orientation.

1.5.2. Characteristics of space

Let's summarize the mentioned concepts and terms as follows:

- Homogeneous, isotropic space: Homogeneous surface, Euclidean distance, implicit path.
- Heterogeneous, isotropic space: Heterogeneous surface, distance weighting, no directional friction characteristics, path related to the cumulative weighted distance.
- Heterogeneous, anisotropic space: Heterogeneous surface, distance weighting, directional friction characteristics, path related to the cumulative weighted distance.

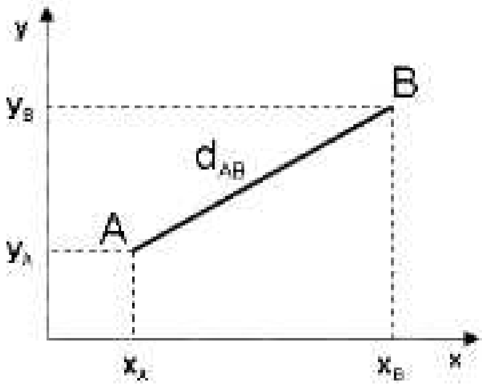
These three levels of modeling are illustrated below. At all levels, the distance is the basis of the measurement of proximity, distance or accessibility. The distance is weighted by the characteristics of the elements. The directional effect is expressed by the variation of the weighting, depending on the orientation. Hence, the gravitational force, considered as a friction element, is considered to be neutral in the case of a transversal path. The moving element may be self driven or driven by an external force. Keep in mind that by modeling the space the 3D reality is reduced to two dimensions. In this example, the third dimension is translated into a thematic component: The friction properties.



Three levels of modeling space properties.

1.5.3. Influence of the dynamics of space on the spatial distance

Modeling the distance depends directly on the metric space. In the Euclidean metrics, the distance between two points is the length of the straight line connecting them. The calculation is based on the coordinates of the two points, cf. illustration below.



$d_{A,B} = \sqrt{(}$

If the path is constrained and the movement cannot follow a linear network and the different segments which the path is composed of have different energy costs (if the coefficient of friction varies from one spatial unit to another), the weighted distance is calculated as follows:

$$d_{A,B} = \omega_i d_i$$

où ω_i est la friction accordée au segment i et d_i la longueur du segment i.

The principle of the calculation is the same as in the case in which the ambler is free to choose his path. The coefficient of friction becomes an attribute of each mesh.

1.6. Glossary

Lambert:
Jean-Henri Lambert, 1728-1777, French mathematician.

Scale:
The ratio between the measured distance on the map and the real distance.

UTM:
"Universal Transverse Mercator" (UTM); Gerhard Mercator, 1512-1594, Flemish mathematician.

1.7. Bibliography

- **Jonathan Iliffe**, 2000. *Datums and Map Projections for remote sensing, GIS and surveying.*. CRC Press LLCBoca Raton, USA: Whittles Publishing.
- **M. Brabant**, 1980. *Topométrie opérationnelle*. Technique et Vulgarisation, Paris.
- **Theriault**, 1994.