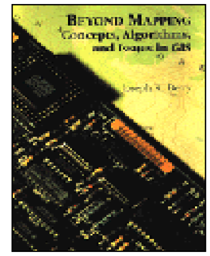
Topic 2 – *Measuring Effective Distance and Connectivity*



***Beyond Mapping* book**

<*Click here*> *for a printer-friendly version of this topic (.pdf).*

(***Back to the Table of Contents***)

You Can't Get There from Here

(GIS World, September/October 1990)

(***return to top of Topic***)

Measuring distance is one of the most basic map analysis techniques. However, the effective integration of distance considerations in spatial decisions has been limited. Historically, distance is defined as "the shortest straight-line distance between two points." While this measure is both easily conceptualized and implemented with a ruler, it is frequently insufficient for decision-making. A straight line route may indicate the distance 'as the crow flies', but offer little information for the walking crow or other flightless creature. It is equally important to most travelers to have the measurement of distance expressed in more relevant terms, such as time or cost.

Consider the trip to the airport from your hotel. You could take a ruler and measure the map distance, then use the map scale to compute the length of a straight-line route— say twelve miles. But you if intend to travel by car it is likely longer. So you use a sheet of paper to form a series of 'tick marks' along its edge following the zigs and zags of a prominent road route. The total length of the marks multiplied times the map scale is the non-straight distance-- say eighteen miles. But your real concern is when shall I leave to catch the nine o'clock plane, and what route is the best? Chances are you will disregard both distance measurements and phone the bellhop for advice-- twenty four miles by his back-road route, but you will save ten minutes. Most decision-making involving distance follows this scenario of casting aside the map analysis tool and relying on experience. This procedure is effective as long as your experience set is robust and the question is not too complex.

The limitation of a map analysis approach is not so much in the concept of distance measurement, but in its implementation. Any measurement system requires two components— a standard unit and a procedure for measurement. Using a ruler, the 'unit' is the smallest hatching along its edge and the 'procedure' is shortest line along the straight-edge. In effect, the ruler represents just one row of a grid implied to cover the entire map. You just position the grid such that it aligns with the two points you want measured and count the squares. To measure another distance you merely realign the grid and count again.

The approach used by most GIS's has a similar foundation. The unit is termed a grid space implied by superimposing an imaginary grid over an area, just as the ruler implied such a grid. The procedure for measuring distance from any location to another involves counting the number of intervening grid spaces and multiplying by the map scale-- termed shortest straight-line. However, the procedure is different as the grid is fixed so it is not always as easy as counting spaces along a row. Any point-to-point distance in the grid can be calculated as the hypotenuse of a right triangle formed by the grid's rows and columns. Yet, this even procedure is often too limited in both its computer implementation and information content.

Computers detest computing squares and square roots. As the Pythagorean Theorem, just noted, is full of them most GIS use a different procedure— *proximity*. Rather than sequentially computing the distance between pairs of locations, concentric equidistance zones are established around a location or set of locations. This procedure is analogous to nailing one end of a ruler at one point and spinning it around. The result is similar to the wave pattern generated when a rock is thrown into a still pond. Each ring indicates one 'unit farther away'— increasing distance as the wave moves away. A more complex proximity map would be generated if, for example, all locations with houses are simultaneously considered target locations; in effect, throwing a handful of rocks into the pond. Each ring grows until wave fronts meet, then they stop. The result is a map indicating the shortest straight-line distance to the nearest target area (house) for each non-target area.

In many applications, however, the shortest route between two locations may not always be a straight-line. And even if it is straight, its geographic length may not always reflect a meaningful measure of distance. Rather, distance in these applications is best defined in terms of 'movement' expressed as travel-time, cost or energy that may be consumed at rates which varies over time and space. Distance modifying effects are termed barriers, a concept implying the ease of movement in space is not always constant. A shortest route respecting these barriers may be a twisted path around and through the barriers. The GIS data base allows the user to locate and calibrate the barriers. The GIS wave-like analytic procedure allows the computer to keep track of the complex interactions of the waves and the barriers.

Two types of barriers are identified by their effects— absolute and relative. *Absolute barriers* are those completely restricting movement and therefore imply an infinite distance between the points they separate. A river might be regarded as an absolute barrier to a non-swimmer. To a swimmer or a boater, however, the same river might be regarded as a relative barrier. *Relative barriers* are those that are passable, but only at a cost which may be equated with an increase in geographical distance-- it takes five times longer to row a hundred meters than to walk that same distance. In the conceptual framework of tossing a rock into a pond, the waves crash and dissipate against a jetty extending into the pond-- an absolute barrier the waves must circumvent to get to the other side of the jetty. An oil slick characterizes a relative barrier-- waves may move through, but at a reduced wavelength (higher cost of movement over the same grid space). The waves will move both around and through the oil slick; the one reaching the other side identifies the 'shortest, not necessarily straight line'. In effect, this is what leads to the bellhop's wisdom— he has tried many routes under various conditions to construct his experience base. In GIS, this same approach is used, yet the computer is used to simulate these varied paths.

In using a GIS to measure distance, our limited concept of 'shortest straight-line between two points' is first expanded to one of proximity, then to a more effective one of movement through a realistic space containing various barriers. In the past our only recourse for effective distance measurement in 'real' space was experience— "you can't get there from here, unless you go straight through them there mountains." But deep in your visceral you know there has to be a better way.

As the Crow Walks

(GIS World, November/December 1990)

(return to top of Topic)

…traditional mapping is in triage. We need to discard some of the old ineffective procedures and apply new life-giving technology to others.

Last section's discussion of distance measurement with a GIS challenged our fundamental definition of distance as 'the shortest straight line between two points.' It left intact the concept of 'shortest', but relaxed the assumptions that it involves only 'two points' and has be 'straight'. In so doing, it first expanded the concept of distance to one of proximity— shortest, straight line from a location, or set of locations, to all other locations—such as a 'proximity to housing' map indicating the distance to the nearest house for every location in a project area. Proximity was then expanded to the concept of movement by introducing barriers— shortest, but necessarily a straight. Such as a 'weighted proximity to housing' map recognizing various road and water conditions effect on the movement of some creatures (flightless, non-swimming crawlers— like us when the car is in the shop).

Basic to this expanded view of distance is conceptualizing the measurement process as waves radiating from a location(s)— analogous to the ripples caused by tossing a rock in a pond. As the wavefront moves through space, it first checks to see if a potential 'step' is passable (absolute barrier locations are not). If so, it moves there and incurs the 'cost' of such a movement (relative barrier weights of impedance). As the wavefront proceeds, all possible paths are considered and the shortest distance assigned (least total impedance from the starting point). It's similar to a macho guy swaggering across a rain-soaked parking lot as fast as possible. Each time a puddle is encountered a decision must be reached-- slowly go through so as not to slip, or continue a swift, macho pace around. This distance-related question is answered by experience, not detailed analysis. "Of all the puddles I have encountered in my life", he muddles, "this looks like one I can handle." A GIS will approach the question in a much more methodical manner. As the distance wavefront confronts the puddle, it effectively splits with one wave proceeding through at a slower rate and one going around at a faster rate. Whichever wave gets to the other side first determines the 'shortest distance'; whether straight or not. The losing wavefront is then totally forgotten and no longer considered in subsequent distance measurements.

As the wavefront moves through space it is effectively evaluating all possible paths, retaining only the shortest. You can calibrate a road map such that off-road areas reflect absolute barriers and different types of roads identify relative ease of movement. Then start the computer at a location asking it move outward with respect to this complex friction map. The result is a map indicating the travel-time from the start to everywhere along the road network— shortest time. Or, identify a set of starting points, say a town's four fire houses, and have them simultaneously move outward until their wave fronts meet. The result is a map of travel-time to the nearest fire house for every location along the road network. But such effective distance measurement is not restricted to line networks. Take it a step further by calibrating off-road travel in terms of four-wheel 'pumper truck' capabilities based on land cover and terrain conditions—gently sloping meadows are fastest; steep forests much slower; and large streams and cliffs, prohibitive (infinitely long time). Identify a forest district's fire headquarters, then move outward respecting both on- and off-road movement for a fire response surface. The resulting surface indicates the expected time of arrival to a fire anywhere in the district.

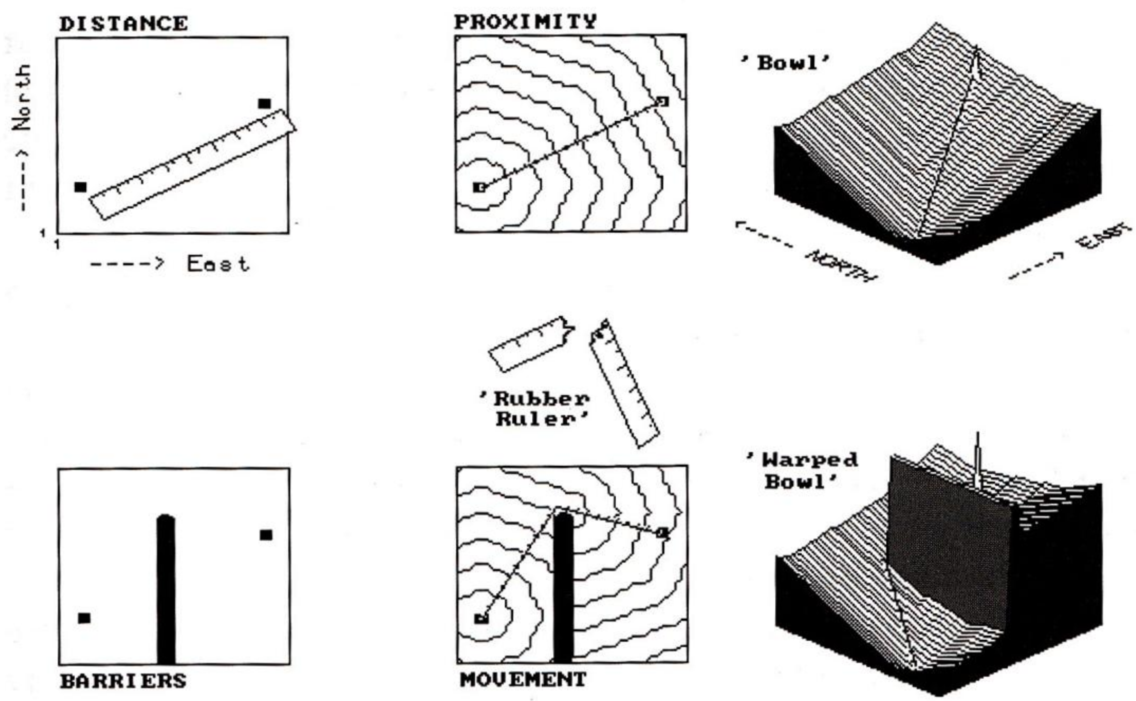


Figure 1. Effective distance is measured as a series of propagating waves.

The idea of a *map surface* is basic in understanding both weighted distance computation and application. The top portion of figure 1 develops this concept for a simple proximity surface. The 'tic marks' along the ruler identify equal geographic steps from one point to another. If it were replaced with a drafting compass with its point stuck at the lower left, a series of concentric rings could be drawn at each ruler tic mark. This is effectively what the computer generates by sending out a wavefront through unimpeded space. The less than perfect circles in the middle inset of the figure are the result of the relatively coarse analysis grid used and approximating errors of the algorithm-- good estimates of distance, but not perfect.

The real difference is in the information content— less spatial precision, but more utility for most applications.

A three-dimensional plot of simple distance forms the 'bowl-like' surface on the left side of the figure. It is sort of like a football stadium with the tiers of seats indicating distance to the field. It doesn't matter which section you are in, if you are in row 100 you had better bring the binoculars. The X and Y axes determine location while the constantly increasing Z axis (stadium row number) indicates distance from the starting point. If there were several starting points the surface would be pock-marked with craters, with the ridges between craters indicating the locations equidistant between starters.

The lower portion of the figure shows the effect of introducing an absolute barrier to movement. The wavefront moves outward until it encounters the barrier, then stops. Only those wave fronts that circumvent the barrier are allowed to proceed to the other side, forming a sort of spiral staircase (lower middle inset in the figure). In effect, distance is being measured by a by a 'rubber ruler' that has to bend around the barrier. If relative barriers are present, an even more unusual effect is noted-- stretching and compressing the 'rubber ruler'. As the wavefront encounters areas of increased impedance, say a steep forested area in the fire response example above, it is allowed to proceed, but at increased time to cross a given unit of space. This has the effect of compressing the ruler's tic marks-- not geographic scale in units of feet, but effect on pumper-truck movement measured in units of time.

Regardless of nature of barriers present, the result is always a bowl-like surface of distance, termed an 'accumulation' surface. Distance is always increasing as you move away from a starter location, forming a perfect bowl if no barriers are present. If barriers are present, the rate of accumulation varies with location, and a complex, warped bowl is formed. But a bowl none the less, with its sides always increasing, just at different rates. This characteristic shape is the basis of 'optimal path' analysis. Note that the straight line between the two points in the simple proximity 'bowl' in the figure is the steepest downhill path along the surface-- much like water running down the surface. This 'steepest downhill path' retraces the route of the wavefront that got to the location first. In this case, the shortest straight line. Note the similar path indicated on the 'warped bowl' (bottom right inset in the figure). It goes straight to the barrier's corner, then straight to the starting point-- just as you would bend the ruler (if you could). If relative barriers were considered, the path would bend and wiggle in seemingly bazaar ways as it retraced the wavefront (optimal path). Such routing characterizes the final expansion of the concept of distance-- from distance to proximity to movement and finally to 'connectivity', the characterization of how locations are connected in space. Optimal paths are just one way to characterize these connections.

No, business is not as usual with GIS. Our traditional concepts of map analysis are based on manual procedures, or their direct reflection in traditional mathematics. Whole procedures and even concepts, such as distance always being 'the shortest straight line between two points', are coming under scrutiny.

Distance Measurement: Keep It Simple Stupid (KISS)

(GIS World, February/March 1990)

*(**return to top of Topic**)*

…but, it's stupid to keep it simple as simplifying leads to absurd proposals (SLAP)

The last two sections described distance measurement in new and potentially unsettling ways. Simple distance, as implied by a ruler's straight line, was expanded to weighted proximity which responds to a landscape's pattern of absolute and relative barriers to movement. Under these conditions the shortest line between two points is rarely straight. And even if it is straight, the geographic length of that line may not reflect a meaningful measure— how far it is to the airport in terms of time is often more useful in decision-making than just mileage. Non-simple, weighted distance is like using a 'rubber ruler' you can bend, squish and stretch through effective barriers, like the various types of roads you might use to get to the airport.

The concept of delineating a line between map locations, whether straight or twisted, is termed 'connectivity.' In the case of weighted distance, it identifies the optimal path for moving from one location to another. To understand how this works, you need to visualize an *accumulation surface*— described in excruciating detail in the last article as a bowl-like surface with one of the locations at the bottom and all other locations along rings of successively greater distances. It's like the tiers of seats in a football stadium, but warped and contorted due to the influence of the barriers.

Also recall that the 'steepest downhill path' along a surface traces the shortest (i.e., optimal) line to the bottom. It's like a rain drop running down a roof— the shape of the roof dictates the optimal path. Instead of a roof, visualize a lumpy, bumpy terrain surface. A single rain drop bends and twists as it flows down the complex surface. At each location along its cascading route, the neighboring elevation values are tested for the smallest value and the drop moves to that location; then the next, and the next, etc. The result is a map of the rain drop's route.

Now, conceptually replace the terrain surface with an accumulation surface indicating weighted distance to everywhere from a starting location. Place your rain drop somewhere on that surface and have it flow downhill as fast as possible to the bottom. The result is the shortest, but not necessarily straight, line between the two starting points. It retraces the path of the 'distance wave' that got there first— the shortest route whether measured in feet, minutes, or dollars depending on the relative barrier's calibration.

So much for review, let's expand on the concept of connectivity. Suppose, instead of a single rain drop, there was a down pour. Drops are landing everywhere, each selecting their optimal path down the surface. If you keep track of the number of drops passing through each location, you have an *optimal path density surface*. For water along a terrain surface, it identifies the number of uphill contributors, termed channeling. You shouldn't unroll your sleeping bag where there is a lot of water channeling, or you might be washed to sea by morning.

Another interpretation is that the soil erosion potential is highest at these locations, particularly if a highly erodible soil is present. Similarly, channeling on an accumulation surface identifies locations of common best paths-- for example, trunk lines in haul road design or landings in timber harvesting. Wouldn't you want to site your activity where it is optimally connected to the most places you want to go?

Maybe …maybe not. How about a *weighted optimal path density surface*... you're kidding, aren't you? Suppose not all of the places you want to go are equally attractive. Some forest parcels are worth a lot more money than others (if you have seen one tree, you haven't necessarily seen them all). If this is the case, have the computer sum the relative weights of the optimal paths through each location; instead of just counting them. The result will bias siting your activity toward those parcels you define as more attractive.

One further expansion, keeping in mind that GIS is "beyond mapping" as usual (it's spatial data analysis). As previously noted, the optimal path is computed by developing an accumulation surface, then tracing the steepest downhill route. …but what about the next best path? …and the next? …or the n^{th} best path? This requires us to conceptualize two accumulation surfaces— each emanating from one of the end points of a proposed path. If there are no barriers to movement, the surfaces form two perfect bowls of constantly increasing distance.

Interesting results occur if we subtract these surfaces. Locations that are equidistant from both (i.e., perpendicular bisector) are identified as 0. The sign of non-zero values on the *differential accumulation surface* indicates which point is closest; the magnitude of the difference indicates how much closer— relative advantage. If our surfaces were more interesting, say travel time from two saw mills or shopping malls, the difference map shows which mill or mall has a travel advantage, and how much of an advantage, for every location in the study area. This technique is often referred to as 'catchment area analysis' and is useful in planning under competitive situations, whether timber bidding or retail advertizing.

But what would happen if we added the two accumulation surfaces? The sum identifies the total length of the best path passing through each location. 'The optimal path' is identified as the series of locations assigned the same smallest value— the line of shortest length. Locations with the next larger value belong to the path that is slightly less optimal. The largest value indicates locations along the worst path. If you want to identify the best path through any location, ask the computer to move downhill from that point, first over one surface, then the other.

Thus, the *total accumulation surface* allows you to calculate the 'opportunity cost' of forcing the route through any location by subtracting the length of the optimal path from the length of path through that location. "If we force the new highway through my property it will cost a lot more, but what the heck, I'll be rich." If you subtract the optimal path value (a constant) from the total accumulation surface you will create a map of opportunity cost— the n^{th} best path map...whew! Maybe we should stop this assault on traditional maps and map analysis and keep things simple. But that would be stupid, unless you are a straight-flying crow.

There's Only One Problem Having All this Sophisticated Equipment

(GIS World, April/May 1990)

(return to top of Topic)

…we don't have anyone sophisticated enough to use it (General Halftrack in the Beetle Bailey comic strip)

As the previous sections have established, distance is simple when we think of it solely in the context of a ruler and "shortest straight line between two points." The realistic expansion of distance to consider barriers of movement brought on a barrage of new concepts— accumulation surface, optimal path, optimal path density, weighted optimal path density, n^{th} best path... whew! Let's get back to some simple and familiar concepts of connectivity.

Take a *narrowness surface* for example— identifying the shortest cord through a location, connecting opposing edges. As with all distance-related operations, the computer first generates a series of concentric rings of increasing distance about a point. This information is used to assign distance to all of the edge locations. Then the computer moves around the edge totaling the distances for opposing edges until it determines the minimum— the shortest cord. For a boxer, the corners of the boxing ring are the narrowest. A map of the boxing ring's narrowness would have values at every location indicating how far it is to the ropes. Small values identify areas you might get trapped and ruthlessly bludgeoned.

But consider Bambi and Momma Bam's perception of the narrowness of an irregularly-shaped meadow. The forage is exceptional, sort of the 'Cordon Bleu' of deer fodder. Its acreage times the biomass per acre suggests that a herd of fifty can be supported. However, the spatial arrangement of these acres may be important. Most of the meadow has large narrowness values— a long way to the protection of the surrounding forest cover. The timid herd will forage along the edges, so at the first sign of danger they can quickly hide in the woods. Only pangs of hunger drive them to the wide-open spaces where Bambi may be lost to wolves; not what you had in mind.

Now raise your sights from cords to rays in three-dimensional space— line-of-sight connectivity, or *viewshed analysis*. Again, concentric rings form the basis of the distance-related algorithm. In this case, as the rings radiate from a starting point (viewer location) they carry the tangent (angle of line between the viewer and a location) that must be beat to mark a location as seen. Several terrain and viewer factors affect these calculations. Foremost is a surface map of elevation. The starting point and its eight surrounding neighbors' elevations establish the initial ring's tangents ('rise to run' ratio, computed as the difference in elevation divided by the horizontal distance). The next ring's elevations and distance to viewer are used to calculate their tangents. The computer then tests if a location's computed tangent is greater than the previous tangent between it and the viewer. If it is, it's marked as seen and the new tangent becomes the one to beat. If not, it's marked as not seen and the previous tangent is still the one to beat.

However, elevation alone is rarely a good estimate of actual visual barriers. 'Screens', such as a dense forest canopy, should be added to the elevation surface. Viewer height, such as a ninety-foot fire tower, also should adjust the elevation surface. Similarly, there may be features, such as a smoke stack and plume that rises above the surface, but doesn't block visual connectivity behind it. At the time of testing whether seen, this added height is considered, but the enlarged tangent is not used to effectively block locations beyond it. Picky, picky, picky... yet to not address the real complexity is unacceptably simplistic. Even more important, is to expand the concept of visual connectivity from 'a point' to 'a set of points' forming extended viewers. What is the 'viewshed' of a road, or a set of houses, or power line or clear cut? In this case, the extended feature is composed of numerous viewing elements (like the multiple lens of a fly's eye), each marking what it can see; the total area seen is the collective viewshed.

Are you ready for another conceptual jump? ...a *visual exposure density surface*. In this instance, don't just mark locations as seen or not seen, but count the number of times each location is seen. "Boy, it would be political suicide to clear cut this area, it's seen by over a hundred houses. Let's cut over here, the views of only a couple of houses will be affected." Or, consider a 'weighted visual exposure surface'. This involves marking each location seen with the relative importance weight of the viewer. "Of this area's major scenic features, Pristine Lake is the most beautiful (say 10), Eagle Rock is next (say 6), Deer Meadow is next (say 3) and the others are typical (say 1)." In this case 10, 6, 3 and 1 is added to every location that is visually connected to the respective features.

Now consider a *net-weighted visual exposure density surface*. "Joe's Junkyard is about the ugliest view in the area (say -10)." If a location is connected to Pristine Point (say +10; Ah!), but also connected to Joe's (Ugh!), its net importance is 0— not as good a place for hiking trail as just over the ridge that blocks Joe's, but still sees Pristine Point.

The previous sections have addressed distance and connectivity capabilities of GIS technology. Be honest, some of the discussion was a bit unfamiliar in context of your current map processing procedures. Yet I suspect this uncomfortable feeling is more from "I have never done that with maps," than "You can't or shouldn't do that with maps." We have developed and ingrained a map analysis methodology that reflects the analog map (an image). In doing so, we had to make numerous simplifying assumptions--like all movement is as straight as a ruler. But GIS maps are digital (spatial data), and we need to reassess what we can do with maps. GIS is more different, than it is similar to traditional mapping.

(Return to top of Topic)

(Back to the Table of Contents)