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Measuring and modeling the speed of human navigation

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ABSTRACT

Navigation, defined here as goal-related movement through space and time to reach a destination, is a fundamental human activity. Geographers, physiologists, archaeologists, anthropologists, and psychologists have long been interested in the spatial and temporal aspects of navigation speed. Hikers, search and rescue teams, firefighters, the military, and many others often navigate on foot through rugged terrain, and their success depends on understanding how the dynamics of foot-based navigation affect individual capabilities.

This research project modeled the speed of movement of human beings engaged in foot-based navigation in wooded environments with varied terrain. Movement models were developed using spatiotemporal analysis of multiple subjects' movement trajectories. Speed estimates were collected via Global Navigation Satellite Systems from subjects while they engaged in foot-based navigation through undeveloped, forested landscapes. Trajectory data from 200 subjects were merged with a land-cover data set to analyze human navigation over varying slopes and terrain. Generalizing these characteristics provided a model of navigational speed of movement from an origin to a destination along an unknown route. Tobler's hiking function and Naismith's rule were used in an analysis of the trajectory data. The model created from this study was shown to outperform those classic human movement speed estimators by predicting route completion time within 10% accuracy ($M = 11.1$ min, 95% CI [9.8, 12.4] min). These models help to explain the human dynamics of navigation.

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Introduction

One of the most basic human tasks is to navigate from an origin to a destination, a task that is accomplished by each of us many times daily. This research seeks to define a model of the speed at which humans accomplish this basic task. Specifically, we investigate navigation in a rural setting where the terrain is hilly and wooded; however, the implications hold for all human navigation on foot.

Models of human walking speed are commonly used in geospatial analysis. Tobler's hiking function and Naismith's rule are simple algorithms built into geographic information system (GIS) software that estimate hiking speeds, such as ESRI's ArcGIS and Geographic Resources Analysis Support System (GRASS). A goal of the current research is to build navigation speed models with improved accuracy, calibrated with measurements of human movement captured in the field.

Hikers, search and rescue, firefighters, the military, and many others navigate on foot through the wilderness. Search and rescue workers have a life-or-death need to understand the time-based range capabilities of a lost person. Hikers use models of speed to estimate and plan

how long portions of their journey will take. Military planning often requires estimating how long a patrol will take when navigating through unfamiliar terrain. The human dynamics of navigation are critical to understanding individual capabilities, requirements, and risks. More accurate models of human navigation on foot will help in better understanding these dynamics.

Navigation

Navigation is defined as coordinated and goal-directed movement through an environment (Montello, 2005). It involves the physical act of movement and the cognitive aspects of deciding upon and following a route. These two components of navigation are classified as locomotion and wayfinding.

Human locomotion during navigation can be accomplished in many ways, such as assisted by a vehicle, bicycle, or in an airplane, but this research focuses on unassisted human locomotion by walking. Locomotion via walking involves body movements governed by muscular contractions. During locomotion, humans make behavioral choices as to where to

step, how to avoid obstacles, and how much effort to expend. These choices and the terrain over which a person is navigating play a large part in determining the speed at which the locomotion is accomplished.

The second component, wayfinding, is a more cognitively centered aspect of navigation. Wayfinding involves planning movement, route selection, continued reassessment of location, and constant decision-making to adjust the route. The use of the sensory processes and the brain require some cost to wayfinding. This component, and the cognition required to accomplish it, decreases a person's rate of movement. There is a difference between someone merely hiking along a known route and someone who is navigating through unknown terrain. Movement speed of navigation is reduced proportionate to the amount of wayfinding that is required. Naismith and Tobler focused predominately on the cost of ordinary locomotion. This research proposes a model of human navigation speed that includes wayfinding requirements, which also impose restrictions on the speed of movement.

Naismith's rule

One of the oldest models for estimating human walking speed over cross-country terrain was devised by William W. Naismith. On 2 May 1892, Naismith set out alone for a hike through the hills and mountains near Crianlarich, Scotland. After completing a 16-km hike and climbing 1920 m in altitude, Naismith concocted his simple formula. The excursion took Naismith six and a half hours to complete. He wrote at the end of his journal entry: "This tallies exactly with a simple formula, that may be found useful in estimating what time men in fair condition should allow for easy expeditions, namely, an hour for every three miles on the map, with an additional hour for every 2000 feet of ascent" (Naismith, 1892). Metric equivalent distances are 4828 m and 610 m. This rule of thumb has been published many times and is still used today to estimate the time required for a given cross-country walk (Langmuir 1984; Aitken, 1977; Clarke, 2015).

Since its inception in the nineteenth century, there have been several efforts to improve Naismith's model. Naismith originally focused on the horizontal and vertical component of the terrain. Others recognized the need to include individual fitness, terrain type, and a downhill slope correction. In 1965, a correction was created by Scottish Mountaineer Phillip Tranter to include individual fitness (Langmuir, 1969). In 1977, Aitken refined Tranter's model to include terrain conditions. He noted that a man can walk at 1.39 m/s (5 km/h or 3 mph) on paths, tracks, and roads but

that this speed is reduced to 1.1 m/s (4 km/h) for all other types of terrain. Later, Langmuir offered further adjustments: He recommended a downhill adjustment, such that speed is variable based on the steepness of the terrain, adjusting Naismith's rule by subtracting 10 min/h for descents between 5% and 12% slope. Finally, he recommended adding 10 min/h when descending slopes greater than 12% since climbing down steep slopes is very slow (Langmuir 1984).

Langmuir's model of human movement speeds is commonly used in GRASS with the r.walk function. The application uses the above mentioned movement dynamics by organizing them into the discontinuous formula:

$$T = a * \Delta S + b \Delta H \text{ Slopes} > 0 \text{ degrees (Uphill)}$$

$$a * \Delta S - 5 < \text{Slope} < 0 \text{ degrees} \\ (\text{Slightdownhill})$$

$$a * \Delta S + c \Delta H - 12 < \text{Slope} < -5 \text{ degrees (Moderate downhill)}$$

$$a * \Delta S + d \Delta H \text{ Slope} < -12 \text{ degrees (Steep downhill)}$$

where T is time in seconds

ΔH is the elevation difference in meters (end elevation-start elevation)

ΔS is the distance traveled

a is the on-road/off-road correction factor (0.72 for on-road, 0.9 for off-road)

b is the correction for uphill movement (6)

c is the correction for moderate downhill (1.9998)

d is the correction for steep downhill (-1.9998)

Speed can then be found using the equation velocity (m/s) = $\Delta S / \Delta T$.

Tobler's hiking function

A second model of hiking was described by Waldo Tobler. Using empirical data provided by Eduard Imhof in 1950, Tobler formulated an equation for walking speed based on terrain slope. The equation yields walking velocity, W (m/s), approximated by:

$$W = 1.67e^{-3.5|S + .05|}, \text{ where } S = \frac{\Delta \text{elevation}}{\Delta \text{distance}} \\ = \tan \theta, \text{ when } \theta \text{ is degrees slope.} \quad (1)$$

Tobler used a correction factor of 0.6 to describe velocity when walking off-road. Despite the equation's simplicity, it remains commonly used in GIS travel time computations (Pingel, 2010; Richards-Rissetto &

Figure 1. Tobler's hiking function.

Landau, 2014; Sherrill, Frakes, & Schupbach, 2010; White & Barber, 2012; White & Surface-Evans, 2012). The QGIS software's walking time function uses Tobler's hiking function as its base theoretical movement model. Remarkably, the walking speed along flat terrain matches Naismith's original rule – 1.39 m/s (5 km/h). The function shows a maximum hiking speed of approximately 1.67 m/s. This speed occurs at a slight downhill slope of 5% (approximately 3°). Figure 1 further illustrates the comparison of walking speed as a measure of slope, based on Tobler's Hiking function (Tobler, 1993).

Naismith's rule and Tobler's hiking function are similar in concept: both consider human movement over space (distance), time, and slope; and both consider downhill movement slightly differently than uphill. Tobler's function is not symmetric around 0% slope, but rather 5% downhill. Naismith's rule was modified by Langmuir to include a downhill correction. Further, the models recognize that movement is different based on terrain type. Each categorize path vs. non-path movement and adjust accordingly (recognizing the Aitken adjustment for Naismith's rule). The variables considered by Naismith and Tobler act as a starting point for the further development of human dismounted navigation models.

Experimental methods

This research collected speed estimates of United States Military Academy (USMA) cadets while they navigated on foot over hilly, wooded terrain as part of their summer training in map and compass navigation.

The estimates provide an opportunity to quantitatively model the contribution of terrain factors to speed during dismounted navigation. The study collected movement, location, and time data using wearable Global Navigation Satellite Systems (GNSS) devices.

Approximately 1000 cadets attend Cadet Basic Training (CBT) each summer at USMA in West Point, NY. Data were collected from 200 volunteer cadets (subjects) who participated in land navigation testing during CBT in July and August 2015. The sample consisted of both sexes at an approximate ratio of 80.5% male to 19.5% female. Subjects wore military field uniforms with a pistol belt and a camel-back hydration system. Subjects who volunteered had varying heights, weights, and fitness levels and were between 17 and 23 years of age.

The primary device used in data collection was a GNSS receiver. The Qstarz BT-1300ST Sports Recorder collected second-by-second location information which was later downsampled to a 10-s temporal resolution. This device was placed in the subject's shoulder pocket so that it would not be lost during the navigational exercise. The GNSS was able to record data for 4 h, which exceeded the length of the navigational test. Its positional data were not available to the subjects during navigation.

The basic data-acquisition strategy was to collect movement information from different people as they navigated over different types of terrain. Subjects were tested on their ability to use a topographic map and a lensatic compass to find seven control points that were placed approximately 400 m apart in less than 150 min. The subjects were scored on their ability to find the correct control points that were identified by an orienteering bag attached to a tree. The per-second trajectory information of each subject was recorded by the Qstarz GNSS device; however, this device was not used to aid navigation.

The military training area where the navigational testing took place falls within the bounding box depicted in Figure 2 (Upper Left Military Grid Reference System (MGRS) Coordinate: 18TWL7573578270, Lower Right MGRS Coordinate: 18TWL7848976111). The red line represents a typical path that a subject took during their navigational test.

The subjects were given MGRS coordinates of seven different control points to find in the woods. The navigation training area had a total of 36 control points that were identified by different orienteering bags. No subjects had the same groupings of the seven points. After mapping the locations of the points on a 1:25,000 scale topographic map, the subjects planned the course they would take to find the control points during their navigation test. The subjects were given an opportunity

Figure 2. USMA navigation training area.

to verify they had plotted the coordinates correctly on the map.

This research used trajectories of 200 subjects who participated in the training on 8 different days. All subjects started the navigation study from the same starting point. There was a temporal spacing of 1–5 min between individual participants. No subjects started closer than 1 min apart and there were approximately 30 min between the time the first and the last subject started on a given day. After leaving the start point, the subjects began the training by navigating toward their first control point. When they found their first control point (or what they thought was their control point) they scanned a radio frequency identification (RFID) card on the electronic scoring device that was attached to the orienteering bag. Then the subject proceeded to find the next remaining control point. After finding their seven points, they returned to the start point. Subjects had 150 min to complete the course.

The subjects were also assigned a safety partner, another cadet who was instructed to accompany but not assist each subject during completion of the navigational test. Safety partners were simply present to ensure the subject was not alone in the woods and that they were moving safely.

Some subjects did not find all points in the allotted time and some found wrong control points. Nevertheless, all subjects eventually returned to the start point, where they removed the wearable equipment and were scored using the information on the RFID card. Subsequently, the logged movement and location data were downloaded for later analysis.

Land cover classification

Movement modeling requires an understanding of the terrain over which the subjects were navigating. In essence, the entire land area was categorized into two groups: on-road or off-road. Foundation data provided by the USMA Department of Public Works depicted the centerlines of roads and trails in the training area. Inspection of 1-m satellite imagery from 2013 was used to validate existence of the roads and trails. An assumption was made regarding how to derive the breadth of the roads on the classed map. A buffer of 9 m from the road centerline created a polygon for the road class and was used to capture some of the GNSS error that occurred when subjects were walking on a road. It is assumed that subjects walking very near (<5 m) the road were most likely walking on the road. A GNSS horizontal error of 4–6 m (RMS) is expected in foliage (Rodríguez-Pérez, Álvarez, & Sanz-Ablanedo, 2007). Using a 9-m buffer helped ensure that most subjects walking on the road were classified as such despite the GNSS error.

Determination of slope and navigation speed

The slope of the terrain over which the subjects traversed and the speed of travel were estimated from the GNSS device outputs. The Qstarz devices saved elevation information of the subjects along with the geographic coordinates. Percent slope was computed by dividing the elevation difference between points by the distance between the points multiplied by 100. Speed was computed by dividing the distance between the

points by the 10-s interval between GNSS readings. These calculations resulted in a data matrix that contained over 130,000 records representing 10-s segments of each subject's trajectory. Each record contained a subject's walking speed, the slope traversed, and either on-road or off-road movement. These records were used to create the model of navigation speed.

Results

This section describes the speeds at which the subjects navigated. Table 1 and Figure 3 describe the general characteristics of the navigation.

The subject's movement speeds were analyzed and a model of human navigation speed developed. First, bins were created every 1% slope between $\pm 100\%$. Then, all trajectory segments with a slope value falling within a bin were averaged. Figure 4 shows the data collected while male subjects navigated on roads. Figure 5 depicts female movement on roads.

Table 1. General characteristics of subject navigation.

Characteristics of subject navigation

Time on the course:

Mean: 141 min

Range: 88–185 min

Distance covered:

Mean: 5655 m

Range: 2358–7603 m

*Seven trajectories began at the start point but did not return to the start point. This is most likely due to a GNSS losing battery power or turning off. These seven trajectories were removed for our summary of the distance and duration of the routes but left in for the modeling effort. These would have significant influence on ranges and means of the overall trajectory summary but would not affect our modeling variables.

Figure 3. Histogram and general description of the subject's speed.

Figure 4. On-road speed of navigation – males.

Figure 5. On-road speed of navigation – females.

Figures 6 and 7 show the data for male and female off-road movement, respectively. In these figures, the black dots represent the bin mean of the speed. The orange line shows movement speed estimates from Tobler's hiking function. The green line shows estimates from Naismith's rule with Langmuir's correction.

The graphical depiction of the data above shows a clear relationship between navigation speed and terrain slope. This relationship can be modeled using an exponential function. The data shown in Figures 4–7 take the form of a normal curve. Equations to fit the data were found by adjusting the parameters of the

Figure 6. Off-road speed of navigation – males.

Figure 8. Irmischer model of on-road navigation speed – males.

Figure 7. Off-road speed of navigation – females.

Figure 9. Irmischer model of on-road navigation speed – females.

normal function to get the best overall match. The Gaussian function was shifted by 0.11 to produce reasonable movement speeds at higher gradients. A separate exponential curve was used to model on-road movement for males (equation 2) and females (equation 3). The models reduce movement speeds by 5% for females (as shown by the .95 scaling factor present in equations 3 and 5). Off-road movement equations for males and females are shown as equations 4 and 5, respectively. The results of the curve fitting are shown in Figures 8–11.

$$Speed(m/s) = 0.11 + e^{\frac{-(Slope + 5)^2}{2 \times 30^2}} \quad (2)$$

$$Speed = .95 * \left(0.11 + e^{\frac{-(Slope + 5)^2}{2 \times 30^2}} \right) \quad (3)$$

$$Speed = 0.11 + .67 * e^{\frac{-(Slope + 2)^2}{2 \times 30^2}} \quad (4)$$

$$Speed = .95 * \left(0.11 + .67 * e^{\frac{-(Slope + 2)^2}{2 \times 30^2}} \right), \quad (5)$$

Figure 10. Irmischer model of off-road navigation speed – males.

Figure 11. Irmischer model of off-road navigation speed – females.

$$\text{where : Slope} = \frac{\Delta \text{ elevation}}{\Delta \text{ distance}} * 100.$$

Visual inspection of the figures indicates that the equations predict the bin means rather successfully. Figures 9 and 11 show more variability than Figures 8 and 10, especially at extreme slopes, due to significantly fewer observations. There were four times as many male subjects as females. Additionally, 95% of the observations were taken at slopes between $\pm 65\%$ slope.

Figure 12. Comparison of predicted vs. actual completion times using the Irmischer algorithm.

The model can be quantitatively assessed by comparing the observed route-based navigation times to the estimated times produced from using speed estimates from the derived model. Estimated route times were produced by applying the derived models to the recorded GNSS slopes of all segments of each subject's movement trajectory. The mean average percent error (MAPE) between estimated and actual route completion times was computed. MAPEs for the male and female groups were both 9%. For comparison, Tobler's hiking function yielded a MAPE of 15% and Naismith's rule produced a MAPE of 20%. Graphical depictions of the results are shown in Figure 12. This plot shows the model deviation from the actual values. If the modeled result exactly matched the predicted route completion time, it would fall on the superimposed line.

Discussion

Similar to eating or breathing, navigation occurs repeatedly throughout the course of a day. This research focused on woodland, wilderness navigation. This form of navigation is characteristic of natural areas with forests, where today few humans live. Forests are used by a variety of people: native tribes navigate to hunt and gather; hikers navigate through forests to visit unexplored areas or get away from society; search and rescue operators often seek lost individuals; and the military uses forests during

operations. This study has focused on the speed at which individuals accomplish this essential undertaking.

Movement speed during on-road navigation was found to follow an exponential relationship over the constrained ranges mentioned above. This study found a general symmetry for navigation speed based on slope with the fastest movement being slightly downhill. This finding is in agreement with Tobler's equation but in contrast to Naismith's formula and research conducted by Minetti, Christian Moia, Roi, and Ferretti (2002) which reported a nonsymmetric relationship. Movement at slightly downhill slope was the fastest, occurring at 5% downhill slope on roads. This is the same as Tobler's estimate of -5% slope. The speed traveled at this grade during navigation is 1.11 m/s for males and 1.05 m/s for females. This is 34% slower than Tobler's function, which estimates the fastest on-road hiking speed to be 1.67 m/s. Naismith's rule with Langmuir's additions predict a top speed more than three times as great. Figures 10 and 11 show the off-road navigation data and the resulting model. The model shows the fastest off-road navigation speed was 0.78 m/s for males and .70 m/s for females. The exponential model for off-road navigation presented here best fits the data with a peak at -2%. Tobler's hiking function estimates the maximum hiking speed for off-road movement to be 1 m/s. Naismith's rule is again significantly higher at 2.1 m/s.

This research was conducted as part of a broader study investigating the energy expenditure of navigation (Irmischer, 2016). The measured times and velocities for the subjects are averages over all of the subjects tested. As USMA cadets, the tested subjects are representative of military personnel. We note that there are likely large differences in navigation speed for different ethnic groups, cultures, and maybe even classes within a single society. Many other variables (weather, load, footwear, temperature, etc.) would also increase this variation. Several other limitations of the study require mention: (1) subjects were not under direct observational control at all times, (2) subjects were not navigating alone, and (3) constraints of the measurement devices likely lowered the precision of the models developed.

In most cases there were ~25 subjects navigating at any given time, which made it unmanageable to directly observe each while they maneuvered through the woods. It was impossible to tell the exact activity of a subject at a given time. For example, activities such as

resting, examining a map, or talking with a friend would all look similar during data analysis. Ideally, parsing non-navigational behavior would be optimal in a study such as this.

The fact that a second cadet was assigned by USMA to travel with each subject as a safety monitor could have had effects on subject's speed of navigation or how they moved. Despite instructions not to interfere or assist with the navigational exercise, it is possible that the subject's behavior was altered by this companion. Perhaps the safety monitor hindered the movement speed or behavior of the subject, or assisted in the navigation. Fundamentally, it is impossible to rule out such interference during the data collection.

Finally, the data collection devices had limited accuracy due to systematic GNSS errors, noise from the receiver, and multipath error from the tree canopy. It is likely that the GNSS produced locational RMS errors near the magnitude of 4–6 m (Rodríguez-Pérez et al., 2007). This amount of error made it difficult to determine if the subjects were navigating on-road or off-road with absolute confidence. Error from the Qstarz device could cause entire segments of data to be misclassified. Additionally, because of receiver and multipath error the elevation and distance estimates used in computing speed and slope can be expected to be inaccurate and could overestimate distances (Ranacher, Brunauer, Trutschnig, Van Der Spek, & Reich, 2016). Misclassification of data segments due to location error and the inaccuracies in the speed and slope estimates are likely explanations for the low goodness-of-fit metrics of the model at micro resolutions. This is a contributing factor to the difficulty in tuning the model at the individual data segment resolution.

Despite these limitations, the model derived in this research replicates the route completion times of the subjects well. The segment level data (10-s resolution) of movement speeds is noisy because of the dynamics of human behavior and the use of GNSS devices under canopy conditions. Nonetheless, using large numbers of movement segments to predict route-based completion time yielded excellent results. For routes approximately 2-h long, the new model accurately estimates completion times within 10 min of the actual time. This is about 50% better than Tobler's function and 100% better than using Naismith's rule.

Tobler's function overestimates the time taken to navigate, primarily because of his model predicting slower off-road navigation speeds, as shown in Figures 6 and 7. Tobler's curve underestimates navigation speed for slopes less than -15% and greater than

5% Also, his model for off-road hiking overestimates navigation speed on the more level terrain between –15% and 5% slope.

Tobler's model for on-road hiking is better at predicting navigation speed overall than his model of off-road estimates. However, similar to his off-road model, his approximations for on-road movement on more level ground outpace the subject's actual movement. It is probable that the subjects are stopping to plan movement, select new routes, and make navigation decisions on more level ground.

Naismith's rule with Langmuir's corrections underestimates the time it took the subjects to navigate from point to point. Figures 4–7 show that almost all of the curve derived from Langmuir and Naismith falls above the empirical data collected during this study, most likely because Naismith's rule is primarily concerned with the speed of locomotion as opposed to the speed of navigation which includes the cognitive cost of wayfinding.

The cost of cognition

In addition to development of a model for the speed of navigation, this research has developed a framework for defining the cognitive cost of navigation. Tobler, and particularly Naismith, primarily estimate the speed of locomotion on differing slopes. When devising their curves, they were not studying subjects undergoing arduous wayfinding tasks. In Naismith's case, he was hiking a known route. Tobler's subjects were Swiss Army soldiers hiking, who were not undertaking challenging navigation from an origin to a destination. Using Montello's theoretical framework of navigation (Montello, 2005), we can devise an equation:

$$\text{Navigation} = \text{Wayfinding} + \text{Locomotion}.$$

Then a framework can be derived to study the cognitive cost of navigation (wayfinding) if navigation speed and locomotion speeds are known.

$$\begin{aligned} \text{Cost of Cognition (Time)} &= \text{Navigation Time} \\ &\quad - \text{Locomotion Time.} \end{aligned}$$

To calculate the cost of cognition, we assume that Naismith's rule or Tobler's hiking function defines the speed of human locomotion. Then, the difference between locomotion and the model derived in this research represents the cost of cognition during navigation. There is a 34% difference between Tobler's maximum speed and the average top speed of the subjects in this study, which can be attributed to the cognition involved in wayfinding. Acts such as map reading, analyzing the terrain, decision-making, assessing one's current position, and determining routes

have costs associated with them and can be quantified using this rationale.

Conclusion

This investigation of the speed of human navigation on foot has developed and tested a model of navigation speed. The measurement devices and the variance of human behavior cause individual segment estimates to be somewhat erratic. However, the vastness of the number of segments along a route mitigates these limitations. Finally, this exploration of navigation, locomotion, and wayfinding has developed a methodology and framework to define the cognitive cost of navigation, which amounted to 34% of the task time in the West Point data. The research has set the groundwork and structure to further study the cost of cognition in the future.

The research presented here offers significant contributions to the fields of GIS and to the navigation modeling community. The models of navigation rates created in this research contribute to a better understanding of the dynamics of navigation. The ability to predict and model the speed of navigation has widespread use. Models of navigation speeds can be used to help wilderness recreation aficionados plan how far they can travel in a day along specified routes. Archaeologists can use these models to predict time-space computations of ancient travel. Back-country search and rescue teams can use the equations to estimate ranges of lost persons. The military will undoubtedly benefit by using these models to plan missions that require overland navigation. While models of hiking in the woods exist, none of these models have addressed the cognitive aspect of difficult wayfinding. Nevertheless, this research has developed a model for human navigation that includes both wayfinding and locomotion.

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No potential conflict of interest was reported by the authors.

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