GRIFFITH OBSERVER

VOL. 82, № 8 • AUGUST 2018 • $2.50

Griffith Observatory's sidewalk solar system is explained on a bronze plaque embedded in the pavement where it widens in front of the north steps. The sun and the orbits of the inner solar system are just beyond the plaque. (photograph David Nakamoto)

FRONT COVER

Lighting the Darkness

The Pharos, the lighthouse said to have been designed by the Alexandrian architect Sostratos and built by the pharaoh Ptolemy II Philadelphus, in the third century B.C., was marvelous enough to be designated one of the Seven Wonders of the Ancient World. This fanciful depiction of what at the time was one of the tallest buildings in the world is one of a set of illuminated images of the Seven Wonders in New York's Empire State Building. These were intended to provide a foundation for the claim the Manhattan skyscraper is the Eighth Wonder of the World. World Wonders, however, are not the agenda of the *Griffith Observer* this month. The lighthouse instead illuminates the mysteries of the first accurate measure of the size of the earth by Eratosthenes of Kyrene. Dr. Dennis Rawlins dispenses with the celebrated well of Eratosthenes at Syene, in upper Egypt, and explains how Eratosthenes could have gotten the right answer by knowing how far from the lighthouse an observer loses sight of the flame. (cover design Robert Smith, photograph E.C. Krupp, 12 May 2000)

Did Eratosthenes Err by Air?

Dr. Dennis Rawlins

In astronomy's history, it is hard to beat the charm of the tale of the first successful estimate of the size of the earth. The measurement is credited to Eratosthenes of Kyrene, who in the third century B.C. headed the celebrated Library of Alexandria. Most general histories of astronomy and astronomy textbooks explain how he established the circumference of the earth by knowing the sun struck the bottom of a deep and vertical well at local noon on the summer solstice at Syene. Syene is the old name for Aswan, in southern Egypt, and some imaginative sources placed the well of Eratosthenes on nearby Elephantine Island.

According to tradition, Eratosthenes measured the zenith displacement of the noon summer solstice sun at Alexandria, about 500 miles due north of Syene. That angle and the actual distance between Alexandria and Syene, as the story goes, allowed Eratosthenes to calculate the circumference of the earth in *stadia* (or *stades*). This technique was famously demonstrated by Carl Sagan in the first program of the original *Cosmos* television series (1980). To show how this worked, Sagan placed a couple of pins on a flat map of ancient Egypt and then bent the map to show how the curvature of the earth points the pins in different directions.

Exploration of the Universe, Dr. George O. Abell's astronomy textbook, dominated the college market for decades, and although it retold the Eratosthenes narrative, it warned readers, "It is not possible to evaluate precisely the accuracy of Eratosthenes' solution because there is doubt as to which of the various kinds of Greek stadia he used."

Of course, the *Griffith Observer* has told the story of Eratosthenes, most recently in "Sizing Up the Earth before Columbus Sailed," by Fred F. Kravath, in the January, 1988, issue.

This month, astronomer and historian Dr. Dennis Rawlins deals with the ambiguities, assumptions, and errors in the canonical Eratosthenes tale and offers an unconventional, unexpected, and effective resolution of the issues that have plagued this fable. There are no shadows, and the well in Syene no longer carries any water for Eratosthenes. If this be true, we are burdened with another mystery. How did shadows and Syene's famous well get dragged into the story of Eratosthenes?

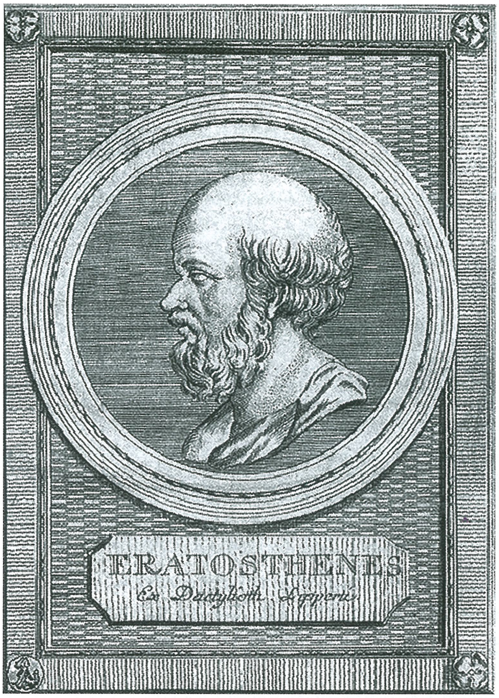
Dr. Rawlins is the publisher of DIO, *The International Journal of Science History*, and has adopted a vigorous, demanding, and skeptical approach to a variety of historical claims, including Peary's and Byrd's reports of reaching the north pole and John Couch Adams's prediction of Neptune. Dr. Rawlins also wishes to remind readers that the high density of the atmosphere of Venus prohibits sunrises and sunsets, that the star 10i Draconis was useful for orienting Egypt's Great Pyramid (the only surviving wonder of the Seven Wonders of the Ancient World), and that there is no ancient evidence for a *stade* 157 meters long.

-ECK

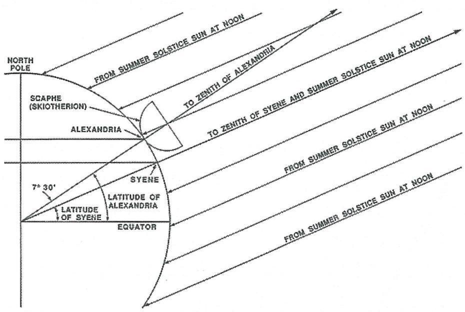
The neverending, wheelspinning debate over what went wrong with two greatly differing ancient estimates of the size of the earth by Eratosthenes and Ptolemy turns out to have a very simple, precise, long-available solution, which some professional historians of science still don't seem to understand.

Two Hugely Disparate Ancient Measures of the Size of the Earth

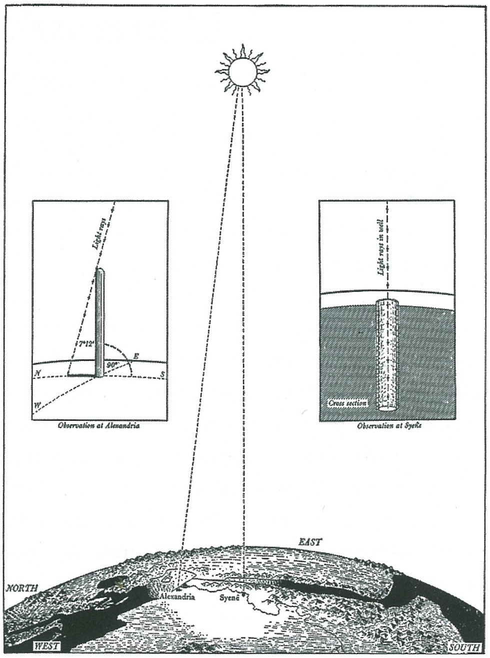
The oldest and perhaps most familiar of the legendary astronomical measurements—which may not be astronomical at all—for the first precise estimate of the earth's circumference, were performed in the third century B.C.E. by Eratosthenes of Kyrene (or Cyrene, near Shahhat, Libya), an Alexandrian Greek. He contended the earth is about 250,000 stades—actually nearer 256,000 stades—around. The measurement was supposedly obtained from observations of the sun at Alexandria and Aswan, far to the south. Many argue that the size Eratosthenes calculated is accurate within a few percent, but because most scholarly opinion



Eratosthenes of Kyrene was an astronomer, mathematician, geographer, librarian, and more, in ancient Alexandria in the third century B.C. His calculation of the circumference of the earth is regarded as the first accurate estimate. A crater on the moon is now named for him. The portrait is a fanciful drawing of an ancient bust said to depict Eratosthenes. (collection Griffith Observatory)



The angle of the summer solstice sun off zenith could have been measured by Eratosthenes at Alexandria with a scaphe, an instrument with a gnomon in an inscribed bowl. At the summer solstice, the local noon sun at Syene, which is on the tropic of Cancer, was straight overhead. (illustration Joseph Bieniasz, Griffith Observatory)

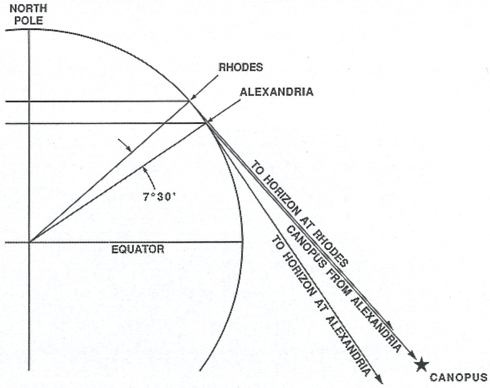


The Greek astronomer Cleomedes provided, likely in the fourth century A.D., the earliest account of the measurement of the size of the earth by Eratosthenes. According to Cleomedes, Eratosthenes knew the sun is directly overhead at Syene, Egypt (Aswan today), at local noon on the summer solstice but a little more than seven degrees off the zenith at Alexandria. At the end of the first century B.C., Strabo, a Greek geographer, had linked the zenith sun at Syene with its deep, vertical wells, at the bottom of which the sun's reflection could be seen. Strabo, however, never mentioned Eratosthenes and his measurement of the earth's circumference. (from *The Story of Maps* by Lloyd A. Brown (New York: Dover Publications, Inc., 1979 reprint; Boston: Little, Brown and Company, 1949)

puts the Greek *stade* at 185 meters, the value 256,000 *stades* is about 19 percent too high.

The persistent alibi for this, more than a century old, invokes a shorter *stade*. Some suggest a *stade* about 157 meters long resolves the discrepancy, but advocates of the short *stade* ignore the fact that in antiquity there were not one but two widely adopted estimates for the circumference of the earth. The second was 180,000 *stades,* which is about 17 percent too

About a century after Eratosthenes, Poseidonius of Apameia, in Syria, attempted to determine the size of the earth by a different method. The portrait bust of Poseidonius is a Roman replica (23 B.C.-14 A.D.) of an earlier Greek sculpture. (photograph Naples Archaeological Museum)



Poseidonius compared the highest elevation of the star Canopus, the second brightest star in the sky, at Rhodes, where Canopus just touched the horizon, and at Alexandria, where it was 1/48 of a full circle, or about 7°30′, above the horizon. This meant the distance from Rhodes to Alexandria was 1/48 of the earth's circumference. (illustration Joseph Bieniasz, Griffith Observatory)

low. This estimate eventually displaced the earlier value attributed to Eratosthenes and was considered the real size of the earth for far longer, over a thousand years. It even influenced Columbus, who was convinced, with a smaller earth, he could reach Ptolemy's Kattigara (Ho Chi Minh City (formerly Saigon), Vietnam) more quickly by going from east to west across the Atlantic. The 180,000-*stade* estimate is thought to have originated with Poseidonios of Apameia, Syria, in the first century B.C.E. It was adopted in the famous *Geography*, authored by Ptolemy, a Greco-Roman Alexandrian, in the second century C.E.

Though hundreds of articles have tried for decades to settle the ambiguities over ancient measurements of the earth by fiddling with the *stade*, three problems prevent the issue from ever being resolved that way.

1-The 256,000-*stades* circumference attributed to Eratosthenes is more than 40 percent larger than the 180,000-*stades* circumference attributed to Poseidonios.

2-Any length for the *stade* that puts Eratosthenes closer to the truth simultaneously makes Poseidonios more wrong and *vice-versa*.

3-All such solutions fit only one of the three quantities in play. They defy the

An ancient well on Elephantine Island, photographed in 1914, was, by then, romantically identified as the well of Eratosthenes. This picture of the well was published in *The Observatory*, but in a letter to the journal's editors, J.L.E. Dreyer, a well-known historian of astronomy, wrote, "There is not the slightest proof that the well on the island of Elephantine, of which a picture appears in your July number, ever had any connection with Eratosthenes." The picture was taken by Mr. C. Lock at the request of Howard Payn, who submitted it to *The Observatory* on 3 May 1914. According to Mr. Payn, the well was known locally as the "well of Eratosthenes." (collection Griffith Observatory)

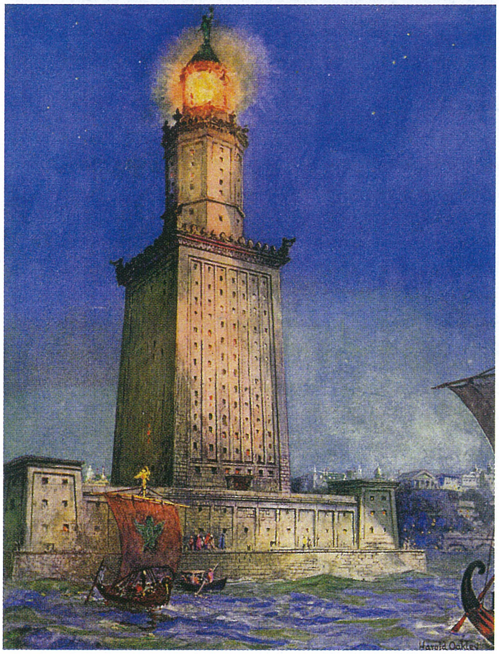
nearly universally accepted value of 185 meters to the *stade* and satisfy, at best, only one of the two widely accepted ancient estimates for the size of the earth.

These difficulties suggest it may be profitable to examine the problem for a solution that avoids metrology and fits all three boundary conditions: the 185-meter *stade,* the Eratosthenes estimate, and Ptolemy's estimate. In fact, such a solution has been available in the professional and popular scientific literature for nearly 40 years. It is not metrological but physical.

Triple-fit Physical Solution

It is commonly thought that the circumference derived by Eratosthenes was based on desert travel between Alexandria and Aswan and measurements of the height of the sun at each city, but that approach would have generated the right answer. For that reason, many believe that the solution lies elsewhere, in a more clever and less laborious method that did not require travel. The fact that the Lighthouse of Alexandria, or Pharos, which was second-most enduring of the Seven Wonders of the Ancient World, was built where Eratosthenes

The "well of Eratosthenes" is still able to catch the zenith sun on the summer solstice on Elephantine Island. The well is just north of what once was the "rest house" for travelers and is now a local museum. There is no evidence Eratosthenese ever traveled to Elephantine Island, much less rested there. (photograph E.C. Krupp, 26 August 1988)



← William Harold Oakley, a British artist, imagined each of the Wonders of the Ancient World in a series of seven paintings. He painted the Pharos in 1933-34 and relied on the reconstruction by Hermann Thiersch, a German archaeologist and art historian, who turned the lighthouse into a Hellenistic skyscraper. (reprinted in *The Seven Wonders of the World* by Paul Jordan, Harlow, U.K: Pearson Education Limited, 2002)

lived *and* when Eratosthenes lived, suggests that he might have used it to make measurements that would permit him to estimate the size of the earth. (Please see www.dioi.org/shg.pdf, G3 for Shakespeare-Marlowe parallel confluence.)

The Pharos was about 300 feet high. Had its designer Sostratos of Knidos wanted to build a lighthouse *exactly* 300 feet tall (certainly a world record in lighthouse height), that would have been very close to half a *stade* (303.4 modern feet). So the square of the limiting distance in *stades* at which the lighthouse flame could

Several nations have put the Pharos on a postage stamp, but Egypt's commemoration of the lighthouse is the most appropriate philatelic acknowledgment and also includes a portrait of its sponsor, the pharaoh Ptolemy II Philadelphus. (collection E.C. Krupp)

be seen would equal the radius of the earth in *stades*. (Please see www.dioi.org/vols/we0.pdf, ‡1 eq. 21.)

Eusebius, the bishop of Caesaria Maritima (in what is now Israel) in the fourth century A.D., implied in his geographical writing a radius of 40800 *stades* for the earth. (Please see www.dioi.org/vols/we0.pdf, ‡1 eqs. 11 & 18.) This happens to be 202 *stades* squared (ibid eq. 24), conventionally rounded to the nearest 100 *stades*. The coast, southwest from Alexandria, is nearly linear, and with the Pharos lighthouse a kilometer off that shore into the Mediterranean, one could measure by odometer that the flame was visible over water out to 202 *stades*.

In fact, the Pharos was not as tall, slender, and elegant as it is usually depicted. Its image on an ancient Alexandrian coin (90-95 A.D.) reveals a shorter, thicker, and less graceful tower. Most estimates give it a height of about 300 feet. The lowest level of the lighthouse was square, and a statue of Triton, a son and merman herald of the god Poseidon, occupied the top of each corner. The middle level was octagonal, it was topped by a cylindrical structure. A mirror at the summit reflected sunlight by day, and a fire there provided the signal at night. The distance at which its summit disappears from view could have been measured on land, along the Mediterranean shore. (from *Pharos* by Hermann Thiersch, 1909, courtesy Dr. Dennis Rawlins)

As I first realized in 2008, multiplying 40800 *stades* by 2π yields a circumference of 256,000 *stades,* which agrees exactly with the circumference I extracted in 1982 from Strabo's Eratosthenes Nile map. (Hugh Thurston. *Early Astronomy.* New York: Springer-Verlag, 1994, p. 120.) Taking the *stade* to be the standard

Ancient models of the Pharos lighthouse, on display in the Greco-Roman Museum in Alexandria, have more in common with the picture on the ancient coin than with the depictions on modern stamps. (photograph E.C. Krupp, 4 September 1988)

185-meter value (D.Engels. *American Journal of Philology* 106: 298-311, p. 309), this is 6/5 times the correct value, or 19 percent too high. In a glaring inverse contrast, the Poseidonios-Ptolemy value, 180,000 *stades*, is exactly 5/6 of the correct value.

There is a shockingly simple common key to the long-intractable mystery of both of these two ancient estimates. If an ancient scientist had accurately measured how far over the sea one could spy the Pharos flame and had done the easy computation of the earth's radius from this, the result would have been wrong on the high side by the factor 6/5 because the bending of horizontal light by air (atmospheric refraction) allows the flame to be seen from a greater distance. The curvature of a horizontal light ray is 1/6 of the earth's curvature. The lighthouse flame idea was known in antiquity. The Roman writer Pliny, in the first century C.E., noted that a lantern hung on the mast of a receding ship disappears when sufficiently distant, due to the earth's curvature (*Natural History* 2.65.164). This approach to estimating the size of the earth does not involve any astronomical observations, just a measurement of the distance at which the lighthouse flame can no longer be seen. Apart from refraction error, that distance is a known fraction of the circumference.

In a second method that requires no nocturnal astronomical observation, two ancient scientists collaborate and compare times of sunset, in clear air, from the base of the Pharos and from the top, which would be later. The difference would be large (more than a minute). Computation of the earth's circumference from

The Pharos of Alexandria is long gone, but the Qait Bay fort was built on its foundations in 1480. (photograph E.C. Krupp, 4 September 1988)

such data would generate an answer too low by 5/6, Refraction again is the source of error. This value appeared long after Eratosthenes because its calculation required spherical trigonometry, which was not available to him. (D. Rawlins. *American Journal of Physics* 47:126-128, 1979, Tables I & II.)

So atmospheric refraction of light can explain both of the old and favored estimates to within one percent, and this is accomplished without the slightest *ad hoc* manipulation of the standard length of the *stade*. The solution simultaneously satisfies all three requisites. Eratosthenes's and Ptolemy's estimates for the size of the earth are explained with the conventional, 185-meter length for the *stade*, all to one percent. (Please see www.dioi.org/vols/we0.pdf, ‡1 eq. 28. An ultra-simplified illustration-by-extremes is provided at www.dioi.org/vols/w23.pdf, ‡8 §§A5&A7.)

Historians of Science *versus* Science

Pieces of the atmospheric refraction solution have appeared for decades in *American Journal of Physics* (1979), *Scientific American* (1979), *Archive for History of Exact Sciences* (1982), *Early Astronomy* (by Hugh Thurston, 1994), and DIO: *The International Journal of Scientific History* (2008). In the 1990s, as opening-page, applied-physics example (with credit to Rawlins), it was presented in the ubiquitous physics textbook, *Fundamentals of Physics*, by David Halliday, Robert Resnick, and Jearl Walker. Despite such broad availability, professional historians of science continue to pursue exclusively fruitless, endless, chimerical stade-scrunching metrological searches, *e.g.* Isis, December, 2016, lead article, which attacks DIO for the "delusion" that Greek scientists were accurate, but has its own delusions (www.dioi.org/islg.doc, D), *e.g.* on differentiating between addition and subtraction and between solar and lunar eclipses.

Meanwhile, historians of science unanimously ignore the atmospheric refraction solution and the doubly verified Eratosthenes value of 256,000 *stades* for the circumference of the earth and do not mention either, even in citations and discussions of the articles that explicitly recommend them. No historian has ever indicated awareness that the 6/5 atmospheric refraction factor has been standard in navigation manuals—*e.g.* the Bowditch *American Practical Navigator*—for over a hundred years. Astronomers can make up their own minds as to whether historians or scientists ought to write astronomical history when it involves mathematical science.

passes about ½° north of the star on the 15th. The moon is in the neighborhood of Jupiter on the 16th.

Saturn (mag.+0.3), in Sagittarius the Archer, crosses the meridian about two hours ahead of Mars. Saturn's transit in the south is at 10:25 p.m. on the 1st and at 8:23 p.m. on the 31st. Through telescopes, the northern face of Saturn's magnificent ring system is seen tipped toward us by almost 26° from edge-on. The moon passes near Saturn on the 20th.

Uranus (mag.+5.8), in Aries the Ram, is close to the meridian at the start of astronomical twilight. On the 15th, it can be found, with the aid of binoculars or telescopes, at the position RA 2^h 2.1^m dec +11° 50'.

Neptune (mag.+7.8), in Aquarius the Water Bearer, transits the meridian, high in the south, at 2:27 a.m., on the 15th. A telescope is required to find Neptune at the coordinates RA 23^h 8.9^m dec -6°33'.

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SPECIAL EVENTS

A partial solar eclipse on August 11th is visible from the extreme northeast coast of Canada, and from Greenland, Iceland, northern Europe, and much of Asia. Its maximum will occur at 09:46 UT (2:46 a.m., PDT) on the northern coast of eastern Siberia, where the moon will cover 0.74 of the sun's diameter, a fraction known as the eclipse magnitude. The entire eclipse runs from 08:02 UT (1:02 a.m., PDT) and 11:31 UT (4:31 a.m., PDT). This follows a total lunar eclipse, centered on Madagascar, which occurred on July 27, and a shallow partial eclipse (magnitude 0.34) that happened over the southern coast of east Australia, Tasmania, and the coast of East Antarctica on July 13th.

The timing of the new moon is very favorable for observing the peak of this year's **Perseid meteor shower** from the night of the 12th to dawn on the 13th. The meteors, which appear to stream from the constellation Perseus the Hero, may be seen from about 10:00 p.m. until dawn starts at 4:40 a.m. By dawn, the numbers of meteors visible could reach about 70 per hour when observed from ideal conditions, far from urban light pollution. Perseid meteors can be seen from mid-July to about August 24.

Comet 21P/Giacobini-Zinner is circumpolar all month. It will move from Cassiopeia the Queen into Draco the Dragon on the 2nd and then back into Cassiopeia on the 15th. It enters Camelopardalis the Giraffe on the 20th. The comet, which orbits the sun every 6.6 years, should be an interesting sight through small telescopes, when observed from dark-sky sites. Its brightness is expected to increase from magnitude 8.9 to 7.5 over the course of the month.

A public star party with telescopes provided by the Los Angeles Astronomical Society and the Los Angeles Sidewalk Astronomers will take place on the front lawn of Griffith Observatory from 2 p.m. until 9:45 p.m. on Saturday, August 18.

Griffith Observatory provides free public observing day and night–weather permitting–through a variety of telescopes. To plan a visit to the Observatory, please see our website (www.griffithobs.org) or call our Program Information line at (213) 473-0890. The Sky Report also provides weekly observing information, and is available at the web site or can be heard by calling (213) 473-0880.

BACK COVER
Geodetic Flame

Topped by a statue of either Zeus or Poseidon, and not King Kong, the Pharos lighthouse of Alexandria actually looks a little like Manhattan's Empire State Building in a drawing by Harry Neal Baum for *My Book of History, Volume II, Conquests* (Chicago: The Bookhouse for Children, 1930) by Olive Beaupré Miller. Although the Empire State Building is 1454 feet high to the top of its antenna, the most likely height for the Pharos was about 300 feet, but we have to rely on reports nearly nine hundred years old for this information. The lighthouse was damaged by earthquakes as early as the tenth century, and by the fifteenth century it was gone. Some of its monumental stones fell into the East Harbor of Alexandria and were discovered in 1968. Elsewhere in this issue, Dr. Dennis Rawlins offers an alternate method for the measurement of the true size of the earth by Eratosthenes, and it makes use of the Pharos. (collection E.C. Krupp)

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