TITLE:

ANCIENT EGYPTIAN ENGINEERING: A STONE BALL-BASED TRANSPORT SYSTEM FOR MOVING LARGE STONE BLOCKS

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Abstract

This paper describes a system involving the use of stone balls that may have allowed the Ancient Egyptians to transport, and load onto river barges, large stone blocks (LSBs) for use in construction projects. The widely held idea that LSBs were always transported on sleds moving over water-lubricated roadways is challenged. It is here proposed that LSBs could have been rolled over stone balls lain at the sides of stone-flanked roads, the outward lateral displacement of these balls prevented by this stone flanking, and their inward displacement prevented by a frame fixed to the bottom of the LSB. Archaeological finds of such flanked roads, as well as abundant dolerite balls, provide evidence that the proposed system could have been used.

One Sentence Summary: An energy-efficient system for transporting large stone blocks for building pyramids etc.

Introduction

This work proposes an energy-efficient system via which the Ancient Egyptians may have moved the large stone blocks (LSBs) —which sometimes weighed hundreds of tonnes— required for their grand architectural projects, i.e., the erection of pyramids, obelisks and colossal statues, etc. It is currently widely accepted that LSBs were moved on sleds pulled along water-lubricated roads. Such a system, however, would have been subject to many inefficiencies —not least problems of friction and water supply— that the proposed model does not suffer.

Figure 1 shows the components of the proposed stone ball system. It is suggested that LSBs travelled over dolerite balls held in position by the walls of stone-flanked roads. The outward lateral displacement of these balls would have been prevented by this stone flanking, and their inward displacement prevented by a wooden frame fixed to the bottom of the LSB (ropes attached to the frame would pass longitudinally over the top of the load). The LSB could then be easily pulled or pushed, and the balls reused by placing in front of the moving block those over which it had already travelled.

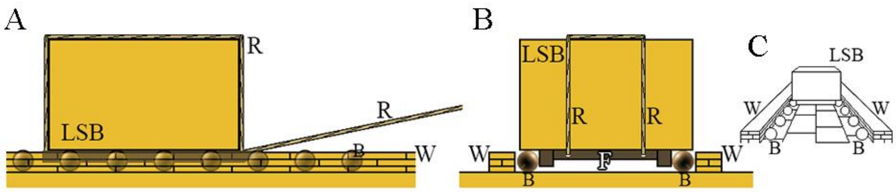

Fig. 1. The proposed stone ball system. A. Side view; **B**. Front view; **C.** View in perspective. B = dolerite ball; W = wall flanking road; F = Frame; LSB = large stone block; R = rope

Archaeological evidence exists for all the components that would have been required by such a system. Numerous dolerite balls have been found in Ancient Egyptian quarries (Fig. 2), but have generally been assumed to be have been pounders (1, 2), i.e., hammerstones for cutting and working rock. Arnold (1) reports the existence in many quarries of spherical (or almost spherical) dolerite balls with a diameter of (mostly) 15-30 cm and a mass of 4-7 kg, respectively. In addition, numerous examples of stone-flanked roads (3) (paved and unpaved), the functions of which have never been satisfactorily explained (3,4), are also known. Figure 3a shows such a road running from the pharaonic quarries on the western bank of the Nile at Aswan; Figure 3b shows a ramped, stone-flanked road to the southeast of the Pyramid of Cheops (1).

Fig. 2. Dolerite balls from the area of the pyramids of Amenemhat I at Lisht. Long thought to be pounders, the proposed system suggests some could have been used in transport.

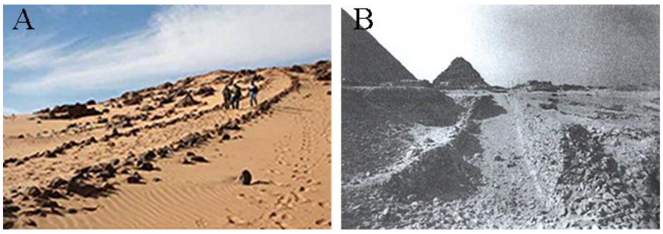

Fig. 3. Stone-flanked roads in Egypt. A. A stone-flanked road leaving the pharaonic quarries on the west bank of the Nile at Aswan. **B.** A ramped, stone-flanked road near the Pyramid of Cheops.

For the proposed system to work, the roads involved would have to have been of constant width. Maintaining constant dimensions, however, seems to have been of great importance to Egyptian road builders. For example, the oldest paved road in the world, which runs 11 km from the Old Kingdom Quarry at Widan el-Faras to the now disappeared Lake Moeris at Qasr el-Sagha (5), has a constant width of a 2.10 m (or four cubits in the Ancient Egyptian system of measurements).

The aim of the present work was to provide proof of concept that the stone ball system is an energy-efficient method of moving LSBs. The results show it could have been an excellent alternative to dragging heavily loaded sleds over water-lubricated roads, the widely accepted method by which LSBs were moved by the Ancient Egyptians.

A scale model of the proposed system

The proposed system was modeled by mounting a granite slab of dimensions 130 cm x 80 cm x 5 cm (mass approximately 140 kg) on a wooden frame (mass approximately 20 kg) with lateral beams measuring 7 cm x 7 cm in cross section (Figure 4 shows a 'blueprint' of the system). For practical reasons, the granite slab was attached to the frame using rawls and screws (not by ropes as the Egyptians would have attached an LSB to the frame), thus allowing the load to be easily increased.

The granite slab, plus its frame, was then laid on a eight granite balls (diameter 11 cm), positioned, four on each side, against the insides of the granite walls (height 5 cm) flanking a concrete roadway (length 15 m, width 76.4 cm). The outward displacement of the balls was prevented by the granite flanking, and their inward displacement prevented by the lateral beams of the frame fixed to the bottom of the granite slab (see Fig. 1).

Loads were then prepared on pallets consisting of 70 granite tiles (60 cm x 40 cm x 2 cm), weighing approximately 870 kg in total. One pallet of tiles was first placed on the granite slab. The total load (i.e., frame + granite slab + pallet with tiles) was 1030 kg. Attempts were then made to push the slab with its load of tiles along the roadway, sliding over the balls. This load was then increased to 1900 kg by adding a second pallet of tiles. Volunteers repositioned to the front of the moving load the 'spent' balls over which it had already travelled. Given the reduced size of the model, no further loads were added for work safety reasons.

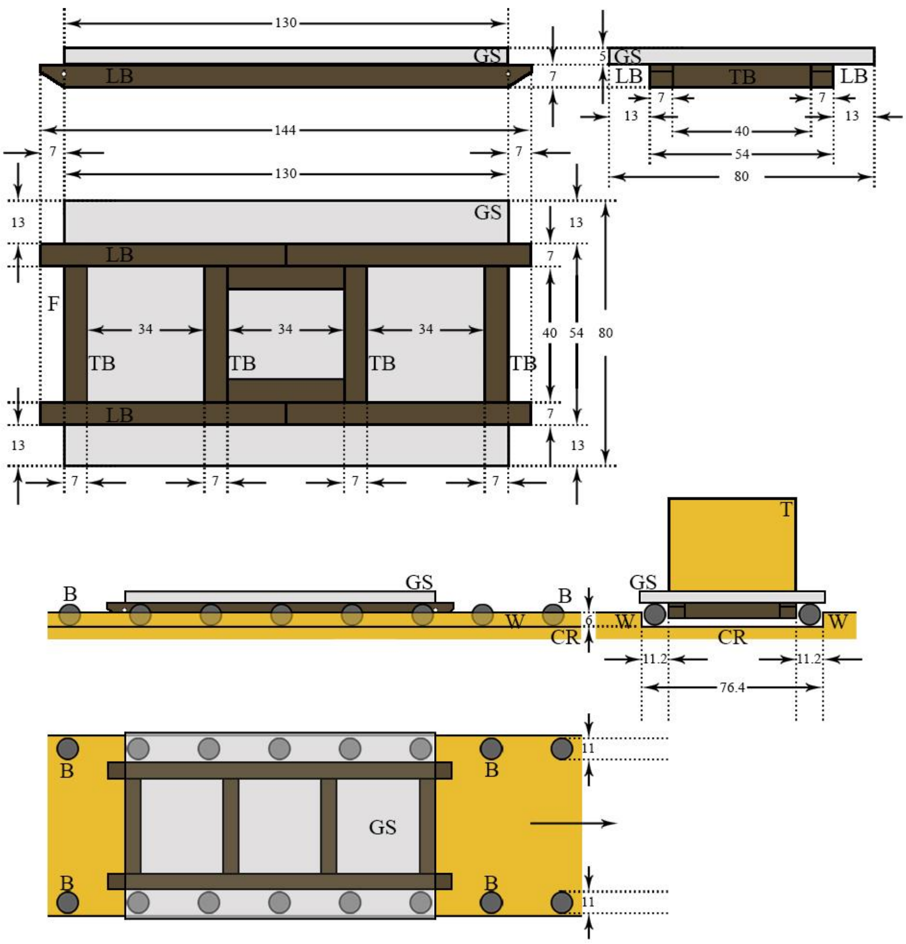

Fig. 4. The proposed system showing the dimensions of its required components. B = Granite ball; W = wall flanking concrete road; F = Frame; GS = granite slab. CR = concrete road; LB = lateral beam of the frame; TB = transverse beam of the frame; T = tile load. All dimensions are in centimeters.

Figure 5 shows the proposed system in operation during the experimental work. Figure 6 shows a graphic abstract of the stone ball-based transport system.

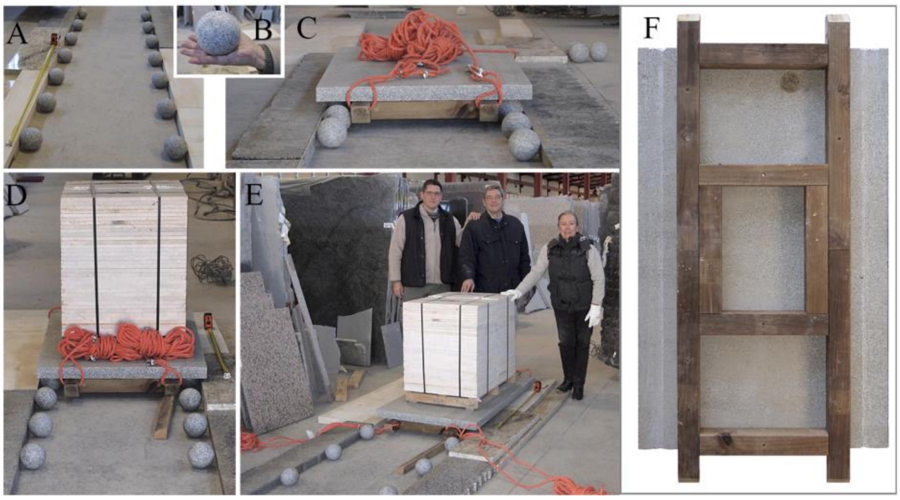

Fig. 5. The proposed system being tested. A. Cement 'road' and granite balls in position, ready to take the load; **B.** One of the granite balls (compared with those found by Arnold [Fig. 2]); **C.** Granite slab with the frame attached to its lower face, in position over the granite balls; **D.** The device, with a load of 1030 kg, ready to be moved; **E.** Side view of loaded device; **F.** View of the lower face of the granite slab showing the frame in place.

Several images show ropes attached to the frame for pulling the device along (these were not actually required in the present tests since the device was easily pushed).

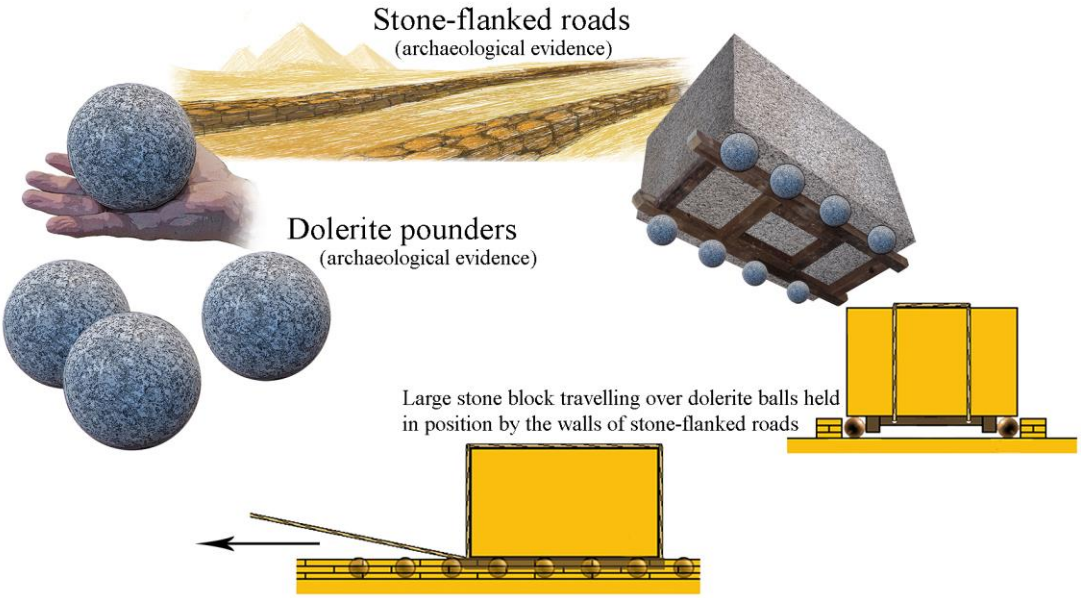

Fig. 6. Graphic abstract of the stone ball-based transport system.

Results

Both experimental loads (870 and 1900 kg) were very easily moved. The inertia of both was easily overcome by a single volunteer, and only hand needed to then push them along. In fact, so easy was it to move them that the speed at which the dolerite balls could be collected from behind and placed in front for re-use (only 14 balls were available) became the limiting factor to the forward progress that could be made.

Discussion

The present work provides proof of concept that the stone ball system provides an energy efficient method for moving heavy loads. In the present work, a load of 1900 kg was moved by a single person with very little effort. The speed of displacement was limited by the ability of the volunteers to reposition the stone balls; walking speed could easily have been attained with further practice or if more balls had been available.

As shown by the archaeological evidence, all the materials required to make the device were available to the Ancient Egyptians, and it is here suggested that this system may have provided an alternative, or complement, to the method of dragging loaded sleds over water-lubricated roads (the most widely accepted method of LSB transport).

The present model provides a possible new use for the dolerite balls discovered at Egyptian archaeological sites. Despite the indication of Junkers (6) that these may have been used in transport, most authors have commonly thought them to be pounders (1, 2). Kelany (2) indicates, however, that although pounders with a diameter of up to 15 cm could be wielded by workers with one hand, it was more likely that two hands would be required, and that while pounders of 40 cm diameter might be picked up by a strong man, two men would probably be needed to use such a tool efficiently. The use of these balls as pounders therefore seems rather difficult. In fact, they may have been even harder to use since both Arnold (1) and Kelany (2) underestimated the mass of the balls they examined. For example, Arnold, affirms that dolerite balls of 15 and 30 cm diameter would have masses of 4 and 7 kg respectively (1); such values however, would require densities of 2.26 g/cm^3 and 0.49 g/cm^3 respectively, very different to those normally described for granite or dolerite. Assuming them to be made from dolerite (as Kelany indicates), and assigning a more suitable density of $\rho = 2.99$ g/cm^3, these balls would have a mass of 5.3 kg and 42.3 kg respectively. Kelany, who studied some 1419 dolerite pounders, surprisingly never weighed them either. Rather, he also calculated their masses, and unfortunately also made errors. Mass is the product of volume and density, as described by the equation $m = V.\rho$, but Kelany seems to have simply used $m = V$. His masses are therefore notable underestimates of the true values. Table 1 shows the errors resulting from these calculations, and the corrected results.

Diameter of dolerite ball	$Ø_1$= 5 cm	$Ø_2$= 14 cm	$Ø_3$= 21 cm	$Ø_4$= 30 cm	$Ø_5$= 40 cm
Volume of dolerite ball	V_1= 0.065 l	V_2= 1.437 l	V_3 = 4.849 l	V_4= 14.137 l	V_5= 33.510 l
Mass of dolerite ball according to Kelany	m_1= 0.65 kg	m_2= 1.44 kg	m_3 = 4.85 kg	m_4= 14.14 kg	m_5= 33.51 kg
True mass of dolerite ball	m_1=0.196 kg	m_2= 4.3 kg	m_3= 14.5 kg	m_4= 42.3 kg	m_5= 100.2 kg

Table 1. Errors committed by Kelany in his calculation of dolerite ball mass, and the correct values.

Thus, balls of such great mass may have been impossible to use as pounders, even by men working in pairs or groups. Junkers (6) has suggested that they may have had a transport function, and have been placed under LSBs to facilitate their movement. The present model provides a means of controlling that transport and maximizing its efficiency.

The proposed system not only provides a function for the stone-flanked roads of Ancient Egypt, but questions the widely accepted idea that LSBs were always dragged on sleds along water-lubricated roads. Experimental work (7) has shown that the movement of a sled can be improved by wetting the sand over which it passes. This compacts it, preventing its build up in front of the sled runners. The authors of the latter article indicate: *we find that there is a pronounced effect of the addition of small amounts of water to sand. The force necessary to move the sled at constant speed with a given weight on top of it can be reduced by as much as 40%, and the force necessary to get the sled to move by up to 70% on standard sand*. They go on to suggest that this method may have been used to transport the Colossus of Djehutihotpe (which weighs 58 tonnes), the mural of which shows a worker on the sled wetting the ground in its path. It also shows 172 men pulling the sled along. In essence, wetting the sand allows the formation of a viscous layer that would support the sled and facilitate its movement. Assuming an optimum state of hydration for the sand on the road surface, the pressure on the runner surfaces in contact with that wet sand would not be able surpass 1.5 tonne/m^2 if the latter were not to escape laterally from below the runners (8). To stay below this critical pressure value, the runners would have required a combined surface area of 38.7 m^2. Assuming a runner width of 30 cm, each would thus have been 64.5 m long. This hardly seems viable. Further, it has been suggested that seven men are required to move a 1 tonne load (some 143 kg per man) on such a sled over a water-lubricated roadway (8, 9). Given that the Colossus of Djehutihotpe weighs some 58 tonnes, 406 men would have been required to pull it along an optimally moistened, flat road. In addition, this system would have required large amounts of water —enough to wet 32 km of road in the case of the transport of the above Colossus—. If a conservative 1 L of water is required to wet the 1 m of road in front of each sled runner measuring 30 cm across, some 64 tonnes of water would have been necessary, even without taking into consideration losses through evaporation and run-off between the stones forming the road. This water too —which weighed more than the Colossus— would have to have been transported to the road. The proposed stone ball system suffers from none of these drawbacks, and at the scale used, allowed nearly 2 tonnes to be moved very easily by a single man. It would likely have been a more efficient system than that described by the above mural.

The positioning of LBSs on the stone balls may have been achieved using loading ramps, such as those seen at the Chephren quarry (Fig. 7). These furrows in the rock, which have one open end, could have been provisioned with stone balls and the LSB (already positioned on the frame) pulled onto them. From here they could have been easily moved along connecting stone-flanked roads.

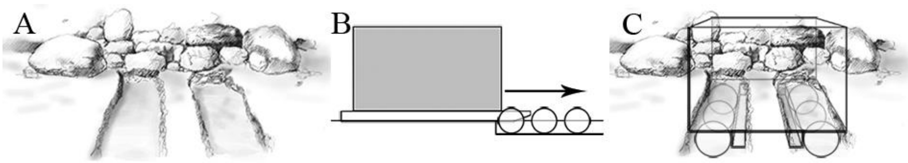

Fig. 7. Possible system for positioning large stone blocks over dolerite balls. A. Loading ramps channels cut into the rock at the Chephren Quarry. **B-C** Positioning of a block over the stone balls placed in the channels.

Hodges (10), through the application of his well-known lever system, asserts to be able of displacing a 2,5 tonnes stone block —the medium weight of the blocks used for the construction of the Great Pyramid— a distance of 19 cm every 20 seconds; which supposes a medium speed of 34 metres per hour. At this speed, a stone block could travel 230 m (the length of one side of the pyramid) in around seven hours. With the LSB system of transport over stone balls, in spite of the lack of skill of the workers who picked and placed the balls in front of the stone block, we were able to displace a 2 ton stone block a distance of 15 metres in 65 seconds. Without remarkable effort, the distance of 230 m could be traveled in just about 16 minutes. Success of the stone ball-based transport system is unquestionable.

The proposed system also provides a means of loading LSBs onto river barges. How barges were loaded with LSBs has long remained an unanswered question. Certainly, the Ancient Egyptians are not known to have possessed crane, pulley or capstan systems. However, by simply preparing a roadway on the barge deck using flanking beams made of wood, thus providing an elongation of the stone-flanked road on land, LSBs could have been easily rolled onto barges.

The walls of the funerary temple of Hatsheput in Deir el-Bahari are engraved with the scene of a barge transporting the two great obelisks that this Pharaoh Queen ordered be erected at the Temple of Amon, and afford an example of how the proposed system could have been used in river transport. To support the weight of the obelisks, the above barge was reinforced with three layers of 24 solid beams below deck (11), the ends of which extended outside the hull (Fig. 8)

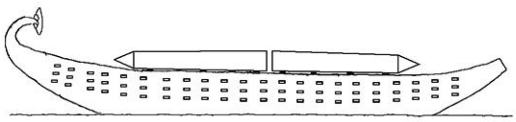

Fig. 8. Diagram of the barge in the mural at the funerary temple of Hatsheput, showing the reinforcing beams protruding beyond the barge's hull.

Figure 9 shows how, under the proposed system (here shown loading one obelisk only), the barge would first have entered a dock (an inlet cut into the river bank), and been moored with ropes to avoid its becoming destabilized under the mass rolling onto it. The supporting beams passing out of the hull would have supplied 144 points at which to attach the necessary ropes (forming the small triangle-like shapes along the vessel's sides in Fig. 9). Loading itself could have been achieved by laying two long, thick wooden beams on the deck, running from the prow towards the stern, to serve as an extension of a stone-flanked road perpendicular to the river's edge (such a road may have been extended, in wood, as a bridge to aid the connection with the barge deck [Fig. 9A]). Stone slabs (to protect the deck) could then have been laid between the newly positioned beams, and stone balls positioned atop them, resting against the inner edge of the beams. The obelisks could then have been simply rolled from the road on land onto the barge (9B-C). After drawing back any connecting bridge, and casting off the mooring ropes, the barge could begin sailing (9D).

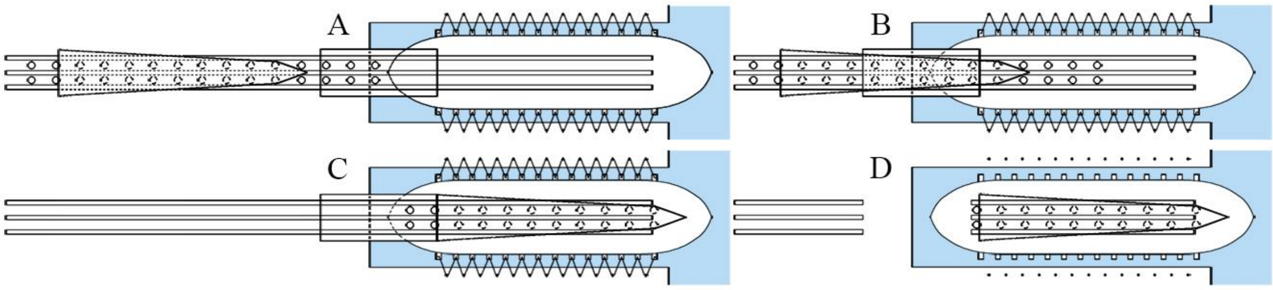

Fig. 9. Mooring a barge and loading an obelisk.

Unloading would be achieved by reversing the operation. Long obelisks, or very large stone blocks, may have required no connecting bridge between the road on land and that set up on the barge deck; the first balls on the deck could have taken the weight of the obelisk as it rolled off the land. Smaller blocks, however, may have required such a bridge be in place.

Conclusions

The proposed stone ball system provides a method by which the Ancient Egyptians may have moved LSBs from the quarries where they were cut to the sites where they were used. The system not only assigns a different use to the dolerite balls found at archaeological sites, it explains the function of ancient stone-flanked roads (as well as their constant width), and provides an energy-efficient alternative, or perhaps compliment, to the use of sleds pulled over water-lubricated surfaces. Not only does it reduce the manpower required to move an LSB, it requires no lubricating water. The proposed system also explains how barges may have been loaded. Further work should examine the efficiency of the proposed system at larger scales, with larger masses, and under different slope conditions. If this system was indeed used by the Ancient Egyptians, the time currently believed necessary to construct pyramids etc., and the manpower such undertakings would entail, would need to be rethought.

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