HISTORICAL DEVELOPMENT OF THE WHEEL

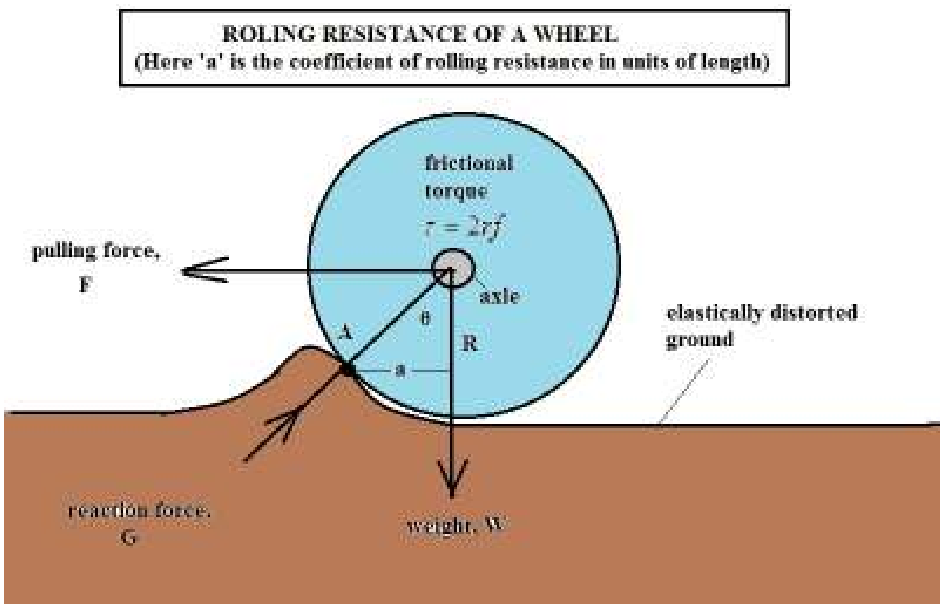
Next to controlled fire, the wheel was clearly early man's most significant invention. It advanced transportation, manufacturing, and warfare significantly and to this day is present in multiple forms from rotary tools, electric generators, trains, automobiles and jet engines to cooling fans in electronic computers and drills used in dentistry. We want here to speculate on how the wheel and all its later refinements were probably invented. It is likely that there were multiple sources for this invention driven by local needs. Certainly pottery wheels and war chariots were in use in ancient Mesopotamia by 3000BC and pictures of wagons found on pottery in eastern Europe, dated via carbon dating , also indicate the early use of wheels in wagons at about the same time. It is our contention that the concept of the wheel predate these times by thousands of years. Here are our thoughts on the matter.

Early man clearly would have been aware of the circular shape of the sun and the moon and the periodicity involved in the movement of celestial objects. Certainly Cro-Magnon man some twenty thousand years ago would also have noticed that certain spherically shaped rocks found along beaches have the interesting characteristic that they roll down inclines. Soon someone would have made a toy using such rocks by inserting an axle into the center of several of such stones. Before long someone else would have come along and recognized that such rolling toys would work even better by replacing the drilled spherical pebbles with round stone or wooden discs in the shape suggested by the full moon and sun as they appeared in the sky. At the dawn of the agricultural age where grain had to be transported considerable distances and large jars were needed for grain storage, it was probably noticed by several clever individuals that wheel toys could be up scaled into the form of a simple steerable four wheeled wagons pulled by horses or oxen. Somewhat later (about 3000BC in southern Russia and in modern day Iraq) it was realized that a two-wheeled wagon drawn by a horse would make the war chariot a formidable instrument of war. To increase the maneuverability of such chariots one would look for ways to make the wheels ever lighter yet be able to maintain their structural integrity. This led to the concept of wooden spokes for disc wheels and thus the true wheel was born. Metal rims to minimize rim wear where also introduced about that time. Pyramid paintings show that spoked wheels on war chariots were in common use by the time of Ramses II in 1270BC. However, the Egyptians were obviously not aware of the use of wheels (or rollers) as a machine a thousand years earlier when the pyramids at Giza were being built.

It is interesting to note that civilizations in the Western Hemisphere never made use of the wheel. This includes the Aztec, Inca, Maya, and the northern American plains Indians . The reason must be that they never had available domesticated draft animals and horses or the availability of level ground for extensive road systems. Toys involving small wheels were familiar to these people but the need to upscale did not exist. Horses were unknown to early South and Central American Indians although the Incas used Llamas for transporting goods along steep trails not suited for wagons anyway. Horses were not introduced to the plains Indians of

North America until after the coming of the Spanish in early 1500 AD. Before that time the only domesticated animal available to them during their yearly migrations were dogs. Buffalo, unlike oxen, apparently could not be domesticated.

Let us briefly look at the rolling properties of the wheel. As one is well aware from introductory high school physics class, there are six simple machines. In order of their probable discovery they are(1) the lever, (2) the inclined plane, (3) the wedge (4) the wheel and axle, (5) the screw, and (6) the pulley(block and tackle). It is the wheel and axle which is connected with functioning wheels used to move a weight W. Here is a look at the relevant forces-



The wheel of radius R rolls about a moving contact point A and moves to the left with speed V=ωR, where ω is its angular velocity. An axle of smaller radius r through the center of the wheel carries a total weight W. In its motion the wheel will elastically distort the level ground (and also distort itself slightly) so that the ground contact point is shifted from directly below the axle to the contact point A shown at distance 'a' to the left. This length 'a' is known as the <u>coefficient of rolling resistance</u> and one typically has a<<R. Also there is a torque opposing the wheel movement due to a frictional forces at the axle. This frictional torque can be estimated from the Coulomb friction formula to be approximately 2rμW, where μ is the coefficient of friction between the wheel and axle. If we now sum the moments about the contact point, we find-

$$FR\cos(\theta) = Wa + 2r\mu W$$

Since the angle θ is very small we can set cos(θ)≈1 to obtain the pull force formula-

$$F = (\frac{W}{R})(a + 2r\mu)$$

It is clear from this approximation that the pull force will be small if the axle radius is small compared to the wheel radius, the axle is well lubricated , and the surface (and possibly the wheel) have very little elastic distortion. Such is the case for wheels on a railroad such as found, for example, between the iron wheels of a train and its iron track. For a simple case let us ask how much force will it take to move a W= 1000 lb weight along a horizontal surface at constant speed when a=2mm, R=1ft, r=1/2 inch and μ=0.1. We find-

$$F=(1000/1)\{[0.2/(2.54 \times 12)]+[2(0.1)/24]\}=1000\{6.66\times10^{-3}+8.33\times10^{-3}\}=15 \text{ lb}$$

So one gains a very large mechanical advantage over competitive methods such as sliding the same weight which would take about a 100 lb pull force for the same μ and W. The invention of modern day roller bearings decreases the opposing torque at the axle even further. Bearings did not come into common use until the 1840s with the coming of the railroads , although Leonardo daVinci discussed wooden bearings much earlier in his 1500 helicopter design. It is interesting to note that the early migrations of Americans to Oregon in the 1830s where mostly by Conestoga wagon which used no bearings but had the wheel hub rotate about a conical shaped skein of metal mounted on a stationary wooden axle. The wheel was prevented from falling off by a large metal cotter pin. Without steel bearings the automobile and aviation industry would not have been possible.

Although it takes relatively little effort to move a heavy weight with aid of wheels at constant speed, it must not be forgotten that a mass M moving at V speed can have a very large linear momentum MV. This means it will take a long time to accelerate a heavy object(such as a train or tanker ship) to a cruising speed and also a long time to come to a stop. A loaded train moving at even moderate speeds can take thousands of feet to come to a halt even when maximum braking is applied. Using Newton's Second Law we have that the deceleration of a train will be –F/M=-Fg/W, where g is the acceleration of gravity. With all of the train's wheels locked so that F has a maximum value of μW , the deceleration would be-

$$\frac{d^2x}{dt^2} = -\frac{\mu W g}{W} = -\mu g$$

This equals just -3.2 ft/sec^2 if μ=0.1. So for the train to come to a complete stop(assuming it does not derail or collide with an oncoming train) will require a distance of s=V^2/2μg equal to 1563 ft if it is initially moving at 68mph. The heat generated in this deceleration process will be intense causing partial melting of the train's wheels and track.

A final aspect of the wheel evolution was the introduction of spokes. These were first used about 2000 BC by the Assyrians for their war chariots. Before that time wheels where constructed from several wooden planks shaped into form of a circle and held together by cross-bars. Such wheels were rather clumsy devices but still served a sufficiently useful purpose for the transportation of grain and other substances. Spokes were undoubtedly invented by someone noticing that much lighter wheels could be built by cutting out part of a wheels cross-section leaving only a few radial support sections connecting the rim and a central hub housing the axle. This soon led to the use of wooden spokes which made wheels much lighter yet still be able to maintain their structural integrity and be much easier to maneuver when employed in a war chariot. Recall that good hard wood (Hickory) can take compressive forces corresponding to about 9,000 psi and a bending stress of about twice this amount. Thus a few spokes of circular cross section of a square inch or so are perfectly sufficient to keep a wheel from collapsing in compression even with loads of several tons.

Tension spokes for wheels were not invented until 1802 by G.F. Bauer. These wheels use multiple wire spokes under tension. Tension spokes together with pneumatic tires and chain drives made practical bicycles possible. Bicycles were the high tech industry of the 1890s and included in its practitioners the Wright brothers who owned a bicycle shop in Dayton Ohio while working on man's first engine driven airplane. All large Ferris Wheels starting with the original wheel at the 1893 Columbian Exhibition in Chicago use tension spokes and look very much like scaled up bicycle wheels. The latest record holder for size is the Singapore Flyer completed in 2008 and having a diameter of 541ft. The longest extant Ferris wheel is the 212ft diameter Riesenrad of 1897 at the Prater park in Vienna. I have ridden on it several times during my European travels. It offers great panoramic views of the city. Some of you may be familiar with it through the movie "The Third Man".