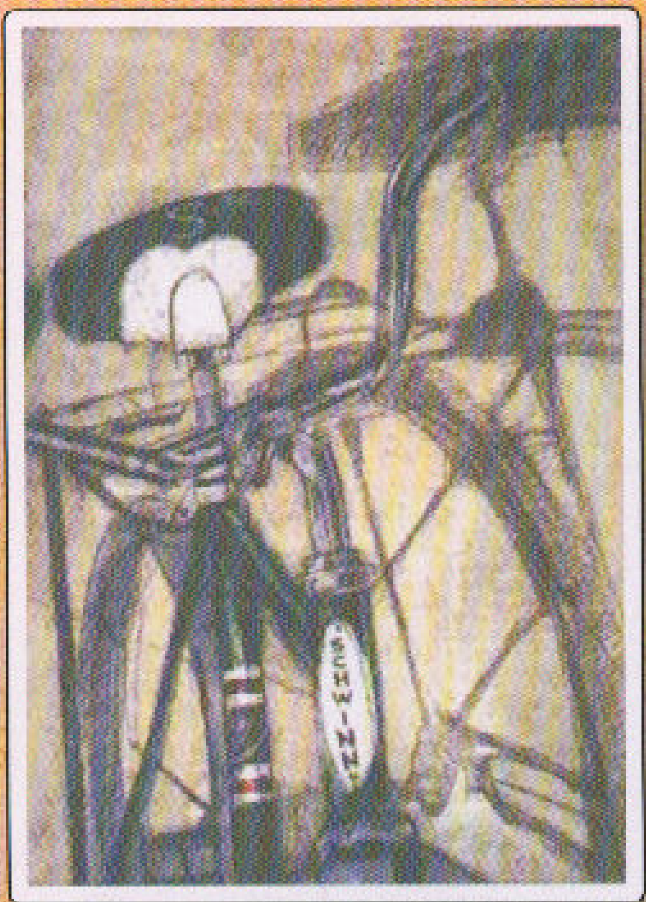
The BICYCLE Story



Vijay Gupta

THE BICYCLE STORY

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While telling the fascinating story of the evolution of the bicycle from its beginning as a crude beam on wheels to its present form of a highly efficient transportation and leisure vehicle, an attempt is made to show how the engineering designs evolved from humble beginnings. This process of evolution of design occurs sometimes slowly and at other times in leaps and bounds, each stage leading to an improved product.

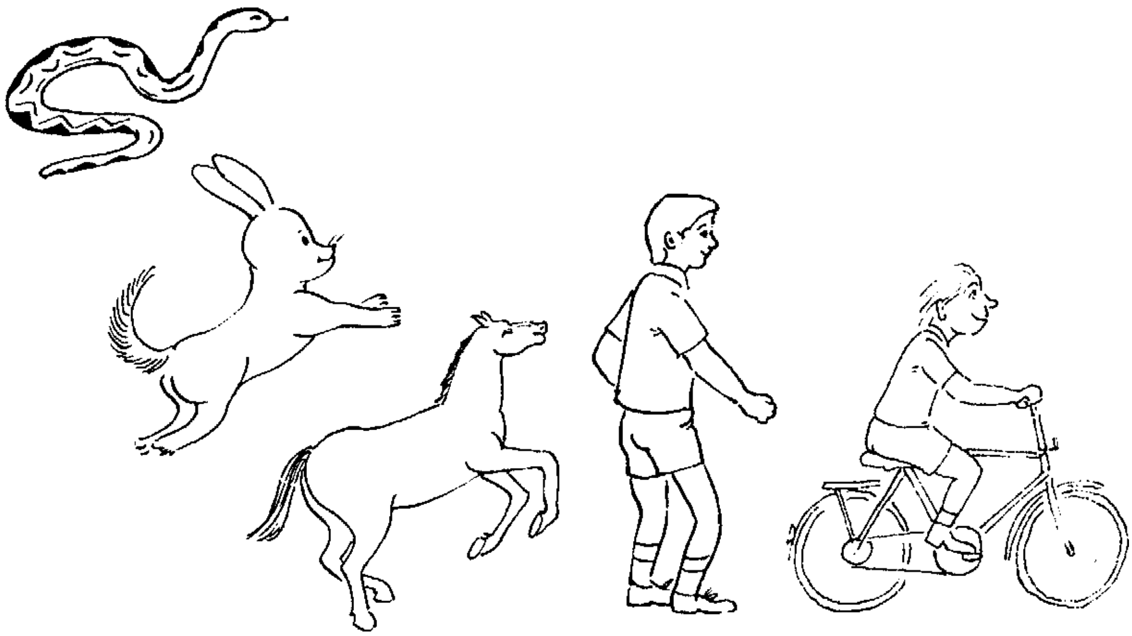
The book utilizes a familiar machine to introduce some essential principles of engineering mechanisms: treadles, cranks, velocity ratio, transmission, gearing, antifriction bearings, triangulation of structures, etc. It also attempts to give a glimpse of the science of bicycling through a discussion of force and power, wind resistance, braking and stability. As an additional feature, some interesting Internet sites connected with the history and science of bicycling are listed for the enthusiasts.

The author, **Vijay Gupta** is Professor of Aerospace Engineering of Indian Institute of Technology, Kanpur. He has an abiding interest in education and education technology. He has produced numerous education videos for the UGC's Country-wide classroom. One of his videos, **The Flying Machine,** won the Best Production Award at the 6th National Video Film Festival in 1993. He has authored a number of textbooks for engineering students and has contributed many general articles to popularise engineering concepts.

The Glorious Machine

Movement is the essence of life. All animals move to find food, attack prey, or escape a predator. Snakes slide, caterpillars crawl, kangaroos hop, horses trot and men walk. Of all animals, humans move the most. Most travel a few kilometres to their workplace and back everyday, go visiting relatives to a city a few hundred kilometres away or travel halfway across the globe to a business meeting. Some travel purely for fun or adventure.

For compulsive travellers humans are not particularly well equipped. A cheetah can out run the best of men by 10 to 1. A horse has much more endurance and consumes only about one-half the energy per kilogram of body weight. But humans design machines which increase their physical capacity. The invention of the wheel is the single most important milestone in the human attempt to increase locomotion. Oxen, horses and camels at first and then steam and gasoline engines increased human movement dramatically. But the idea of using is own muscular effort in driving a wheel has always fascinated man. It is interesting to note that the bicycle was perfected much after railway trains were in full commercial operation and the horseless carriage was just knocking on the doors. Inventors everywhere are struggling even today to perfect a flying machine driven by muscular effort alone —eighty-five years after the first successful petrol-engine powered flight.



A man on a bicycle is far ahead of anybody else as tar as energy efficiency is concerned

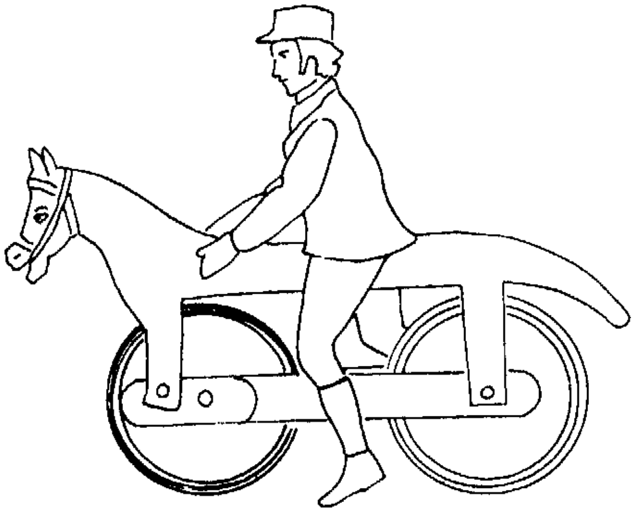
A bicycle is the most efficient vehicle ever designed. Its cost, in terms of energy spent in carrying a comparable load over a comparable distance, is one-tenth that of the most efficient jet aircraft and about one-twentieth of the best automobile.

The humble bicycle has a glorious past. First conceived as a plaything of the rich, it soon evolved into an efficient and convenient means of transport. The coming of the automobile, however, relegated it to a role of an exerciser or a sports-machine, though in large parts of the world, notably China and Southeast Asia, it is still used as the primary means of daily transportation. In the industrialized world it seems to have come a full circle. The bicycle is re-emerging as a vehicle of choice for short runs in urban areas. It does not pollute the atmosphere. It is almost noiseless. It does not take up precious parking space and wide roads. It has been estimated that for distances up to 8 km in city centres a bicycle may be faster than a car given the time taken for taking a car out of a garage, finding parking space and walking from the car park to the place you intend to go. And above all, a bicycle provides you valuable physical exercise while you ride to work.

This booklet narrates the fascinating story of the bicycle and its technological evolution.

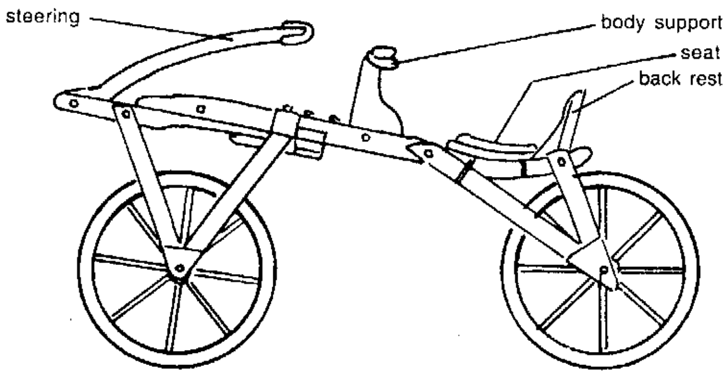
The First Steps

The first mention of a two-wheeled vehicle propelled by the rider himself occurs for a 1791 toy-like machine which was simply a wooden beam on two wheels, one behind the other. The rider sat on the beam and drove the machine by pushing his feet alternately against the ground, as if skating. One could not turn this machine except by lifting and dragging the front wheel to one side. It didn't even stay erect if both feet were off the ground.



A hobby horse was displayed for the first time in 1791 in a Parisian park as a plaything for the rich.

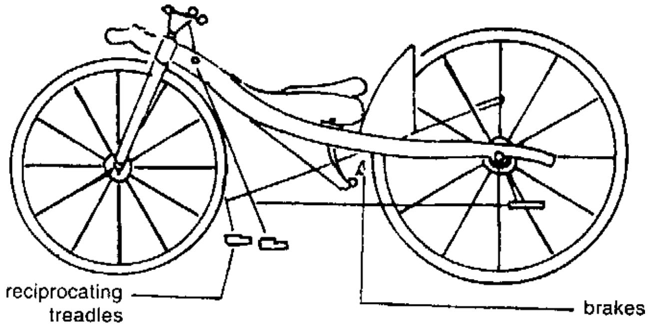
The first notable improvements in this clumsy machine were reported in 1817 when its front wheel was turned by moving a handle. This machine, known by various names such as a hobby-horse, a Draisienne (after the German Baron von Drais, who is credited with this invention) or a velocifere, soon became popular among the rich and fashionable of the day. The steerable front wheel was an important addition, and was responsible for giving the Draisienne some measures of stability. A man on a Draisienne could exceed the speed of runners and horse-drawn carts even for long journeys. But the awkward posture of the rider invited ridicule and the bumpy ride on solid wheels over rough roads resulted in many cases of hernia. This led to a setback in the development of bicycles.



A Draisiene (1817). The steerable front wheel gave it some stability. "Hobby-horses rode in their carriages and walked in the mud at the same time".

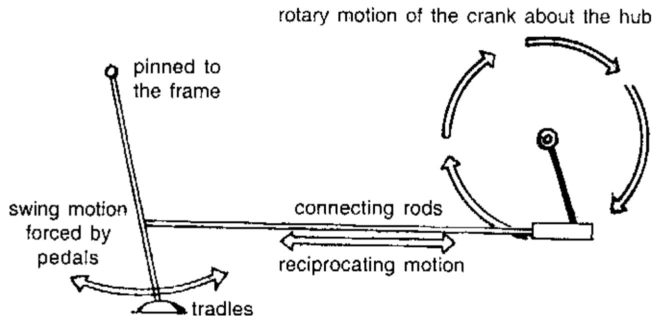
The Treadle and the Crank

The first true bicycle, a machine which could be ridden with both feet entirely off the ground, appeared in 1830. A Scottish blacksmith named Kirkpatrik Macmillan employed the power of the leg muscles to turn the rear wheel directly, instead of dragging the machine by pushing with his feet on the ground. The mechanism used two bars suspended from the front end of the frame. The lower ends of these bars, known as treadles, carried pedals which were driven alternately by feet through short arcs. The motion of these treadles was conveyed through a pair of connecting rods to the rear wheel where they moved two cranks. The cranks converted the push and pull motion of the rods into the rotary motion of the rear wheel.



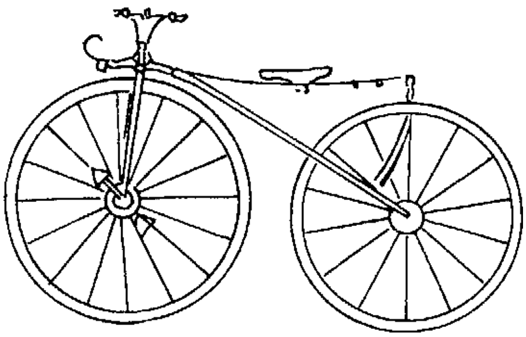
Macmillan's velocipede (1839) was the first true bicycle with feet 'out of the mud'. Not a single one of this was sold, though many copied it.

The treadle-driven crank is a common mechanism in many applications. The common foot-driven sewing machine uses the same mechanism to convert the rocking motion of the foot-plate into rotary motion of the wheel. This arrangement is also similar to the one used to convert the reciprocating motion of pistons into the rotary motion of the crankshaft in a steam or automobile engine.



The treadles drive the connecting rods which swing the cranks through full circles, rotating the wheel. The same motion is used in the treadles of an old-fashioned sewing machine and in the crank of a piston engine.

The velocipede, though a bicycle in the true sense of the word, was never a commercial success and not many persons knew about its bold design. For the following forty years the design of the bicycles stagnated at least in the method of converting the motion of feet into the rotary motion of the wheel.



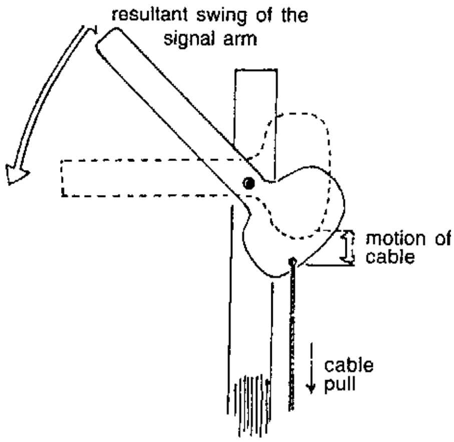
Michaux's velocipede (1863) was the first commercially successful machine. Though very expensive, it created a craze that spread over Europe and America. Due to the dare-devil riding by the rich and the bold, the bone-shaker (as it was nicknamed because of its rough ride) soon drew enough detractors so as to be banished from the road at many places.

The first commercially successful bicycle appeared in 1863. It had a pair of pedals connected to the front wheel and was ridden in the same manner as the basic children's tricycles of today. Its wooden wheels (with iron tyres) on the cobbled roads of the day gave the rider such a rough ride that it was nick-named the bone-shaker.

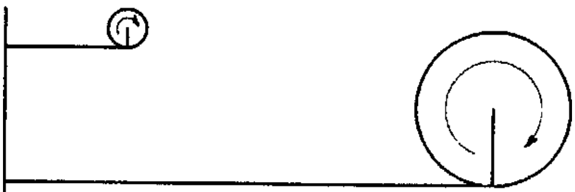
However the bone-shaker was more elegant than its ancestors. It was lighter, faster and a lot more comfortable than the hobby horse. This comfort was achieved by having the seat fixed through a leaf spring which ran from the front handle to the rear wheel.

Velocity Ratio and the Tall Ordinary

One result of the direct cranking of the front wheel was that one cycle of the motion of the legs turned the front wheel only once. This produced a forward motion of the bicycle through a distance equal to the circumference of that wheel only. This was not considered enough for speed. One could of course pedal at a greater rate to move the boneshaker faster, but there was a catch. The power output (i.e., the rate of doing work) of a person pedalling a machine depends upon the force he applies on the crank, and on the rate of pedalling measured in the number of revolutions per minute (or RPM for short). As the RPM increases, the power output will increase, provided the applied force does not change. But it does. Repeated trials have shown that this force decreases as the RPM increases. When the pedals are locked, the force applied is maximum but there is no power delivered (the RPM being zero). There is indeed a value of RPM where the rate of doing work by pedalling is maximum. This value is between 45 and 60 RPM. For a bone-shaker to move at speeds comparable to those of modern bicycles, one would have had to pedal at considerably higher RPM which would not have been comfortable at all.

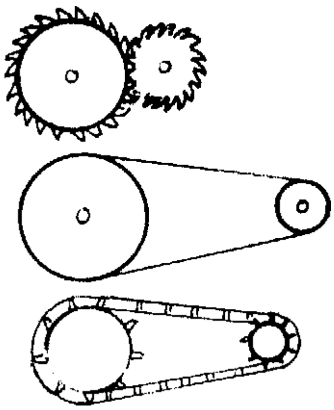


The principle of levers. By keeping 'effort' arm small one can move the 'load' through a larger distance. This is inverse of the usual situation where effort arm is made larger to overcome a larger load by a smaller effort.



A larger wheel covers a larger distance in one revolution.

A simple way to overcome this was to use a larger front wheel. The increased circumference of a large wheel moved the machine through a larger distance in one revolution of the directly cranked machine through a larger distance in one revolution of the directly cranked wheel. This simple principle of increasing the distance travelled (of course, at the cost of reducing the force) can be seen in relation to a simple lever. Consider an old-fashioned railway signal. A relatively small motion of the cable attached to the shorter (effort) arm results in a much larger swing of the signal (which is the "load" arm in the terminology of fevers). Note that the "load" overcome by "effort" is reduced in this same proportion. The ratio of the load to effort is termed as the mechanical advantage. In a bicycle we are interested in increasing the velocity ratio, and the decreased mechanical advantage is the price that we pay for it.



Various methods of obtaining large rates of rotation of a driven wheel—gears, belts and chains. Each method has its own advantages and disadvantages.

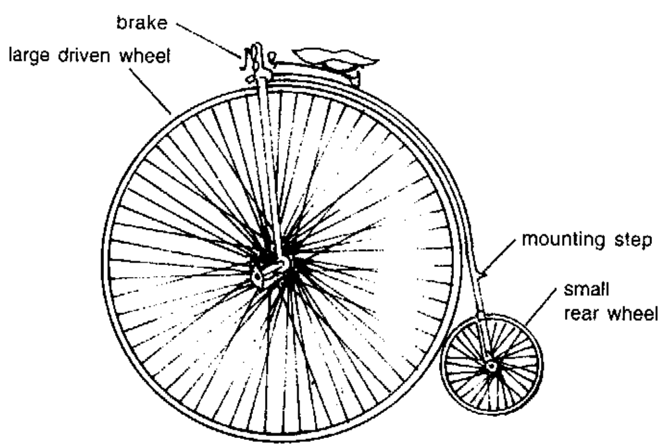
The increased diameter of the front wheel is only one of the ways of obtaining a large velocity ratio. A simple pair of unequally sized gears a belt over two pulleys, or a chain running between a large chain-wheel and a small sprocket (a toothed wheel) are some other ways. In each of these cases the velocity ratio is the ratio of the sizes of the two wheels, gears or sprockets. From the automobile practice, where gears are used almost exclusively for the purpose, the velocity ratio is commonly referred to as the gear ratio.

Each of the above transmissions (that is, the method of transmitting power from the pedals to the wheel while obtaining a mechanical advantage) has its own advantages and disadvantages. For example, the performance of a belt-drive, which depends upon the presence of the resistance to slipping of the belt on the pulley (i.e., of the friction), decreases sharply when the belt becomes dirty, grimy or loose. Gears give better performance, but are more expensive.

But this is getting ahead of our story. As mentioned before, the simplest and the most obvious method of increasing the gear ratio in a bone-shaker was increasing the size of the front wheel. And that is exactly what was done. The front wheel started growing in size, from 36 inches to 48 inches, to 54 inches, and one even had a 64 inch (163 cm.) wheel. The limit on this was imposed by the length of the riders' legs. To keep the weight of the machine low, the diameter of the rear wheel shrank, giving these bicycles their definitive shape, the penny-farthing. (The British coin farthing was four times the size of a penny). These machines were also called the tall-ordinaries or the high-wheels.

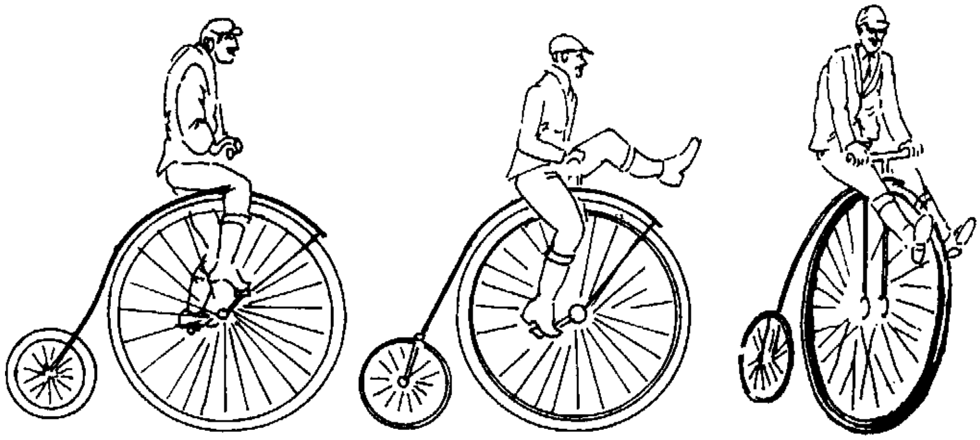
Hazards of High-Wheeling

The tall-ordinaries were not for women, non-athletes or the weak-hearted. Getting on one was not easy with the saddle more than a metre and a half from the ground. One gave the machine a shove, and jumped-up onto the two foot-braces atop the small rear wheel, and then jumped again onto the saddle. Pedalling such a bike was difficult because the distance between the saddle and the lowest point of the crank travel was in many cases larger than the inner length of the leg. Fully-grown men pedalled like a little kid on a modern bicycle too tall for him—leaning heavily on the side his foot goes down, and not being able to sit on the saddle while pedalling. Furthermore, getting off was difficult.

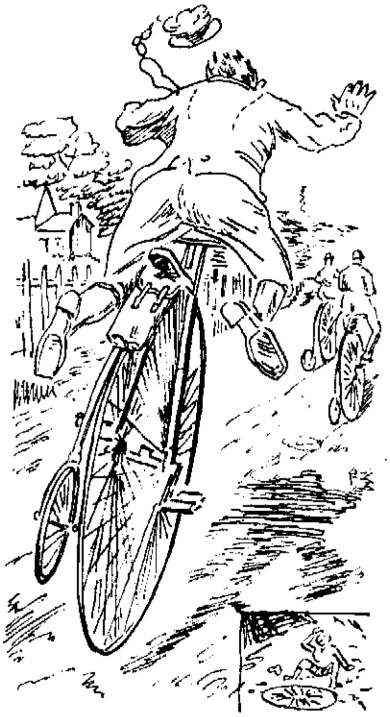


The high wheelers introduced the bicycles to the general public. At least a hundred mounting step thousand of these machines were built. They ruled the roads from 1870 to 1890. This vehicle is credited to be tried first to give the freedom of the road to an individual—even if only to the athletic, brave and male. The diameter of the front wheel grew till it was limited by the length of the rider's legs.

But while atop and coasting, with both feet off the pedals, the rider looked down from his high throne on the world beneath him. The speed of up to twenty miles per hour was more than that of almost anything else on the road, and people got out of his way. But the thrill of speed and the sense of superiority that a rider felt came at a high cost. With the rider atop the big front wheel, the centre-of-gravity was too high and forward for the machine to have stability. Even small obstructions such as a pebble on the road, or a sudden application of the brakes, sent the rider flying face down into dirt. Even experienced riders had mishaps which were frequent enough to give them their own distinctive names of a cropper or an imperial crowner.

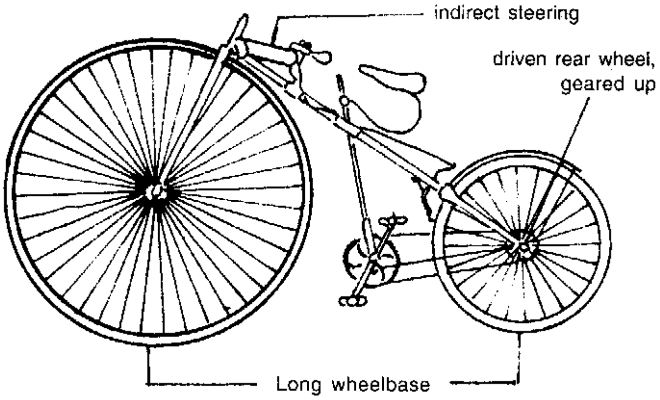


The man hurtling through space perched on a high wheel felt graceful and regal, but it called for extreme skill in 1. Starting a ride 2. Pedalling an oversized wheel and 3. Coasting downhill.



Dogs, pigs, chicken and children, bricks and potholes in the road, all could easily cause the infamous 'header'. So also could a row of bricks, a taut length of string, or a stout rod poked among the spokes. A high wheeler seemed to bring out the worst in people. One could also easily gat a foot or clothing entangled in that great expanse of spoke work that the big wheel was.

Various efforts at increasing the stability of the high wheelers didn't result in any success. A new design was needed. The rider had to be moved back and lower—which was not possible with the basic high-wheel design. One of the attempts at a solution reversed the entire geometry, with the rider now sitting on the enlarged rear driving wheel. But one couldn't pedal the rear wheel directly, unless one sat slightly behind it on an overhang—something impossible because of the reasons of equilibrium. The famous American Star bicycle of 1882 attempted an indirect drive through a system of levers, drums and straps (much in the fashion of treadles). The star had some success in making bicycling safer, but for the next few years the tricycle was the centre of attraction for the inventors and the manufacturers. The British royal patronage also helped popularize the tricycle among fashionable women who were beginning to demand equality with men.

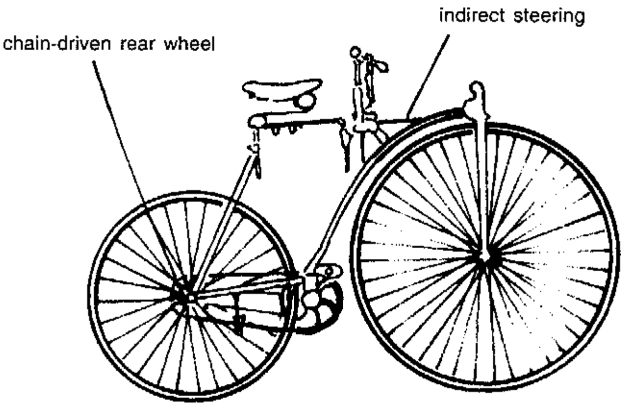


Lawson's chain-driven 'bicyclette' (1879) was the first to use the modem layout of a chain-driven rear wheel. The handle bar is operated through an indirect steering because the seat is placed far in the rear.

The Safety Machine

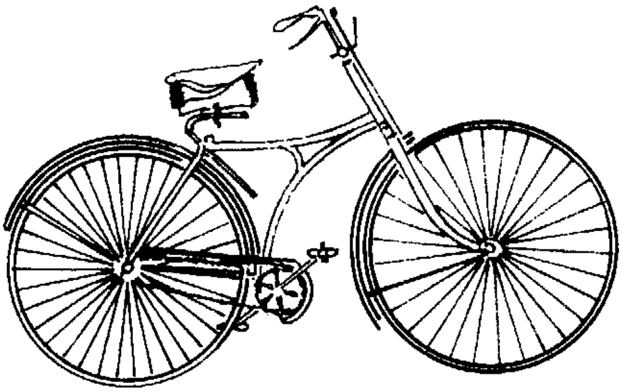
The first machine that closely resembled the modern bicycle hit the roads in 1879.

In these low machines, the rider sat between the two wheels and paddled a low crank which drove the rear wheel through a chain. A large gear ratio was obtained by using a large chain wheel and a small sprocket attached to the rear wheel. This did away with the need for a large driving wheel. The size of the wheel no longer determined the velocity ratio, which could be varied by changing the size of the chain wheels.



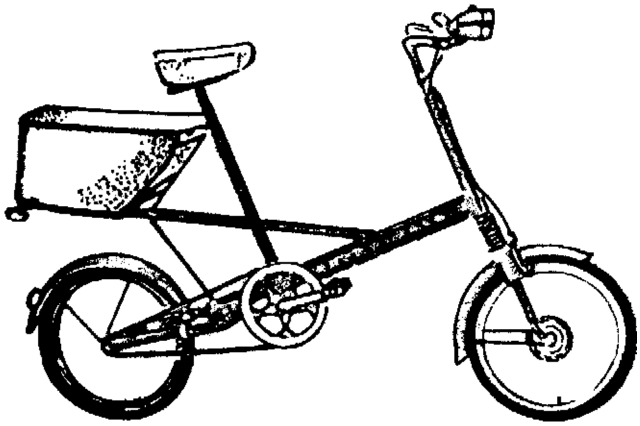
Early Rover Safely bike (1885) also had an indirect steering. It introduced the compact diamond frame which has been the standard till today.

The rider could reach his leg down to the ground in case he lost balance. The low and rearward centre-of-gravity removed the tendency of the machine to come a cropper— even if it ran into a low wall and quite appropriately the bicycle was called a 'safety'.



The later Rover Safety (1889) completed the development of the bicycle form.

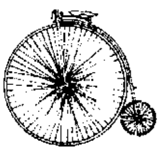
Inspite of the demonstrated safety, this bicycle met with a lot of resistance. Solid-tyred safeties vibrated more than the corresponding high-wheelers, and pedalling so close to the unprepared ground muddied the feet. But with later improvements and continued experience with its qualities, the 'safety' won almost everybody over within 10 years. Since the front steering wheel was unaffected now by the pressures of pedalling, the strain of keeping the machine balanced reduced drastically, so that one could even ride with both hands off the handle bar. These machines carried more luggage, either on the handlebars or on the rear-wheel. Learning to ride one was child's play



Moulton (1967) design is the one major change that has taken place in the last 100 years; it has 16" wheels and a cross-frame. It is easier to handle, more comfortable to ride and fashionable as well.

There were innovations in other design features too. The tubular diamond frame appeared in 1885 and has been an essential feature, largely unchanged till today. This reduced the weight of the bicycle significantly. Air-filled tyres, first fitted in 1888, cushioned the rides dramatically, and by 1890 the safety bicycle had become comfortable and convenient enough to be generally accepted as the conveyance of choice by all including those who earlier considered a bicycle beneath them or who thought their physique to be unsuitable for the rigor of cycling. The bicycles were used by vendors and workers and ladies for afternoon spins. The gentry used it for undertaking tours and exercise and sportsmen for competitive racing.

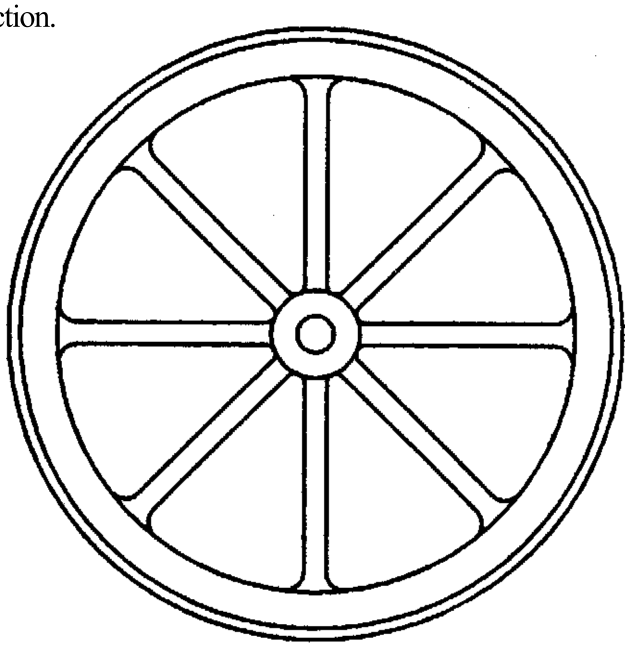
The bicycle has changed little in the last 100 years. The picture of an 1885 Rover safety resembles a modern touring bicycle. There have been some changes no doubt. We use much lighter and stronger materials now. The ball bearings are improved. Calliper brakes are much more effective.



The Parts of a Bicycle

Wheels

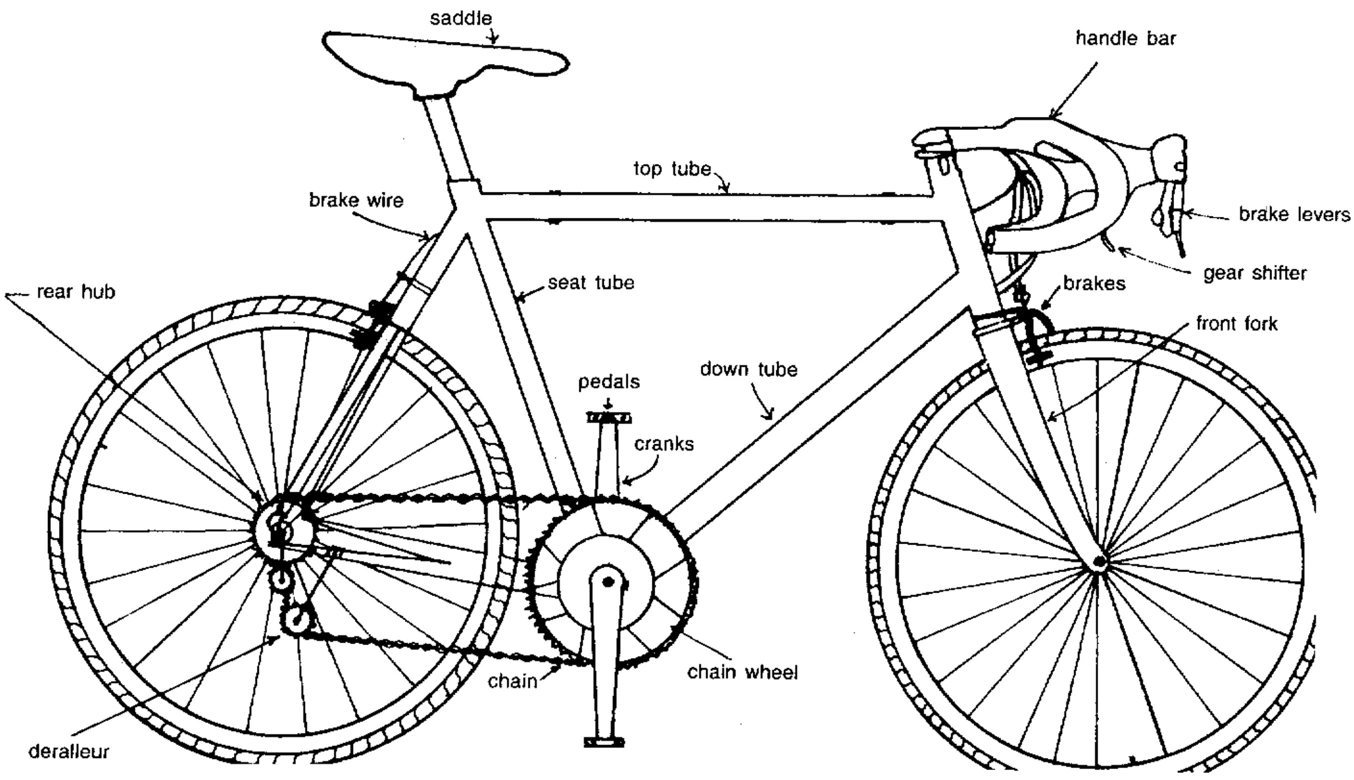
It is often said that the most fruitful source of ideas for a creative engineer is the natural world around him. Evolution has ensured the most efficient solutions to almost all problems that he is even likely to face. In the field of transport, the greatest single invention is the wheel. A cylindrical wheel rolling on a smooth surface offers up to 100 times less resistance to motion than an equivalent weight being dragged on the ground. Humans most probably observed things like stones rolling down surfaces. The inspiration could also have come from logs or other cylindrical objects displaying the mechanics of rolling friction.



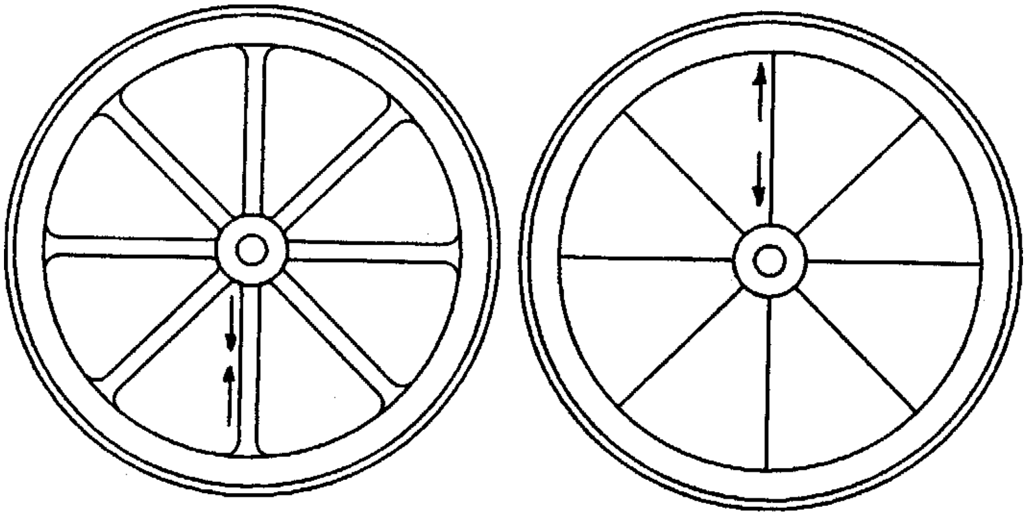
A cart wheel with stout compression spokes.

We know that a steel train wheel rolling on a steel rail-road offers the minimum resistance to motion among all moving things, less than one-thousandth of the weight on the wheel. But when this wheel rests on a soft surface, the surface deforms forming a pit like depression. Further rolling of the wheel would now require a greater effort because the wheel now has to climb out of the pit. Similarly, soft wheel rolling on a hard ground deforms under its load at the point of contact. The 'deformed' wheel is no longer perfectly round and so it can not roll on smoothly. In either situation, the effort required for motion is increased because of the deformation.

The wheels of hobbyhorses and bone-shakers were heavy and similar to those of carts. They had thick spokes of wood which supported the load. The relative inflexibility of the wheels and the spoke resulted in the rider feeling every bump or pebble on the road.



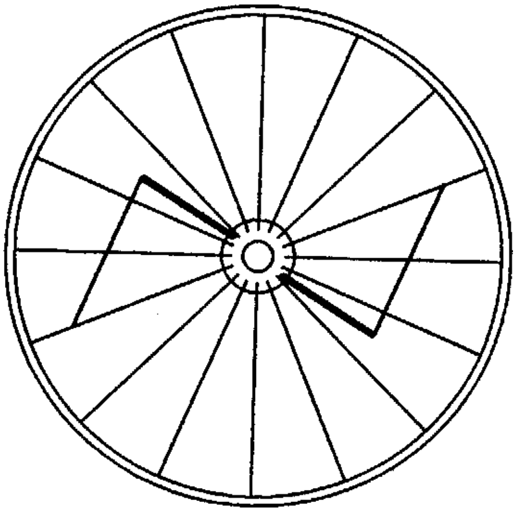
A modern bicycle is a compact assembly of a larger number of carefully tailored parts.



The load applied at the hub is borne in compression by the stout spokes of a cart wheel, but in tension in thin wire spokes.

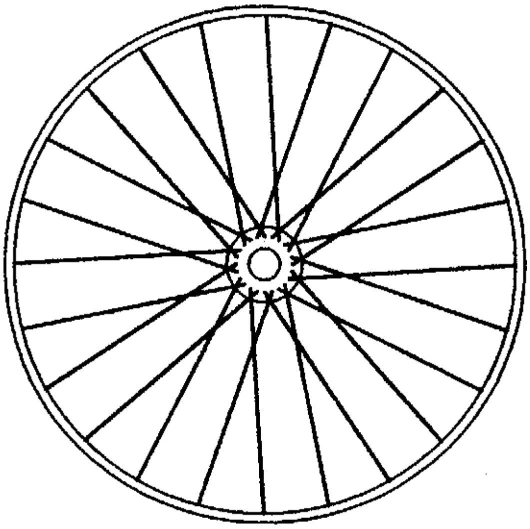
The first real advance in the design of wheels came with the Penny-Farthings.

The design of their wheels was based on the principle of suspension—the load (represented by the central hub) was carried suspended on fine wires from the top portion of the rim, rather than being supported by stout columnar spokes on the lower portion of the rim. We all know that a slender rod can carry a much heavier load when the load is suspended from it (so that the rod is being stretched, i.e., is in tension) than when it props up the load from below (so that it is being compressed by the load). A slender column under compression buckles easily when loaded. This is the principle of construction used in elegant and light rope-or wire-suspension bridges. The thin wire spokes of the new wheels exploited this principle and represented substantial savings in weight.



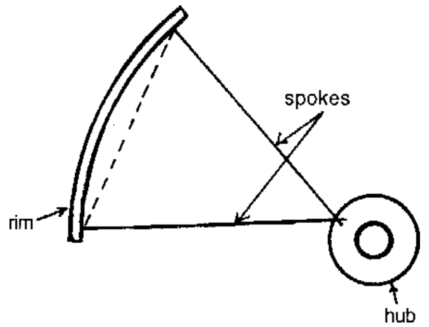
The earlier tensioned-wire spokes ran straight in to the centre of the wheel. These spokes could take the vertical load at the hub but couldn't transmit the torque at the hub to the rim. A couple of rigid bars with their own tensioned spokes were added for the purpose.

The earliest of these wheels had radial spokes which could be tightened to give them an initial tension. By carefully adjusting the tensions in the various spokes, one could make the rim concentric with the hub so that the wheel run true, i.e., without a wobble. But the radial hubs could not transmit the large torques exerted by the pedals at the hub. Any application of torque simply bent the thin spokes. Hence two rigid bars, each with its own tensioned spoke (see wheel of a penny-farthing), were added to the driven wheel making it heavier.



Spokes tangent al the hub is the lightest solution for a wheel. It is restrained in all the six degrees of freedom.

It was not long before these torsion spokes were eliminated through the use of a very innovative way of lacing the spokes at the hub. The spokes, instead of running in radially towards the centre, were now so placed that they were tangential to the hub. When a torque was applied to the hub of such a wheel through its sprocket, the wire-spokes were tensioned, driving the rim in the same direction. A series of triangles formed by the spokes and the hub ensured that all loads were resisted by just the tensioning of spokes. This principle of triangulation of structure was later used in the design of the diamond frame of the safety bicycle.

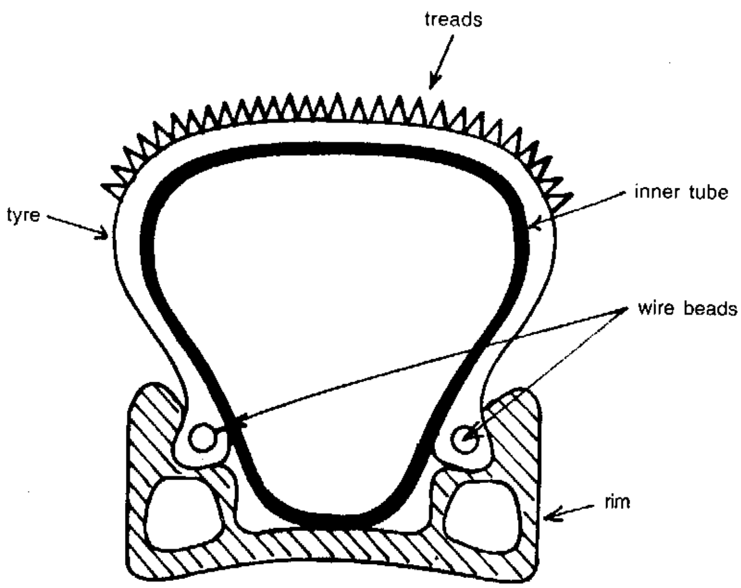


Two spokes and the hub form a triangle: the strongest geometry for carrying a load.

The torques that arose during deceleration were resisted in a similar manner, every alternate spoke ran in tangentially in the backward direction. Application of braking torque was resisted by the resulting tension in these spokes. All modern spoke-wheels have essentially the same design.

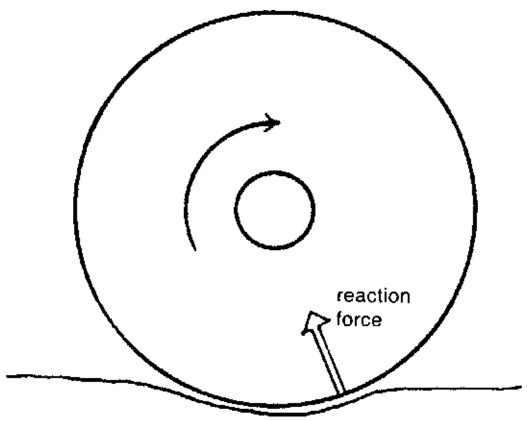
Pneumatic Tyres

The air-filled tyres of modern bicycles were first introduced on the safety bicycle in 1888 as a means of reducing the vibrations that a solid rubber tyre produced. The principle is simple: the bicycle now rode on a pocket of air which cushioned the ride.



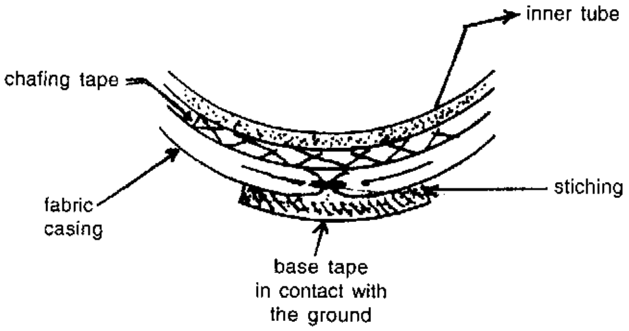
Cross-section of a rim and a conventional wire-bead tyre. Beads are tensioned and keep the tyre in place.

The air is contained in a thin pressurised inner tube which is protected by a thicker outer tyre. The tyre is strengthened by many layers of reinforcing cords embedded in the rubber. It has two steel-wire beads which snap into grooves in the wheel rim. As the inner tube expands under pressure, the tyre bead is pressed firmly in the rim grooves keeping the tyre in place.



When a soft tyre rolls on a soft ground, both the tyre and the ground deform. The deformed ground sets up a reaction force so directed that it resists the motion. Similarly, the deformation of tyre, too, does not permit smooth rolling.

The rolling resistance of the pneumatic tyres arises because of the flexing of the tyre under load. As a loaded tyre rolls on ground, the different portions of the tyres are constantly flexing, dissipating energy. One obvious way to reduce the rolling resistance is to increase the inflation pressure of the tyre. Increased pressure means that the tyre sinks less under the load and, therefore, flexes less. Typical pressures used in modern tyres are between 2.5 to 4 atmospheres (that is, 250-400 kPa or 35-60 psi). Every bicyclist knows that a bicycle runs faster with higher tyre inflation. He also knows that stiffer tyres absorb shocks poorly and that the ride is a lot rougher. All the pebbles and pot-holes on the road appear to be transmitted directly to the saddle.

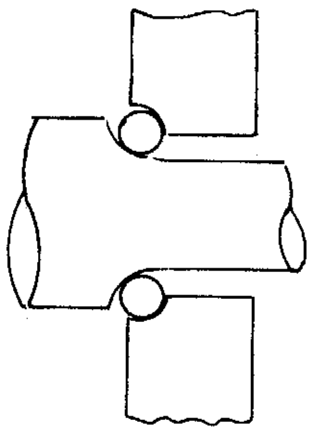


The construction of a tubular. The fabric casing is the main body of the tyre with the inner tube sewn in. A rubber tread is glued to the casing on the outside of the tyre.

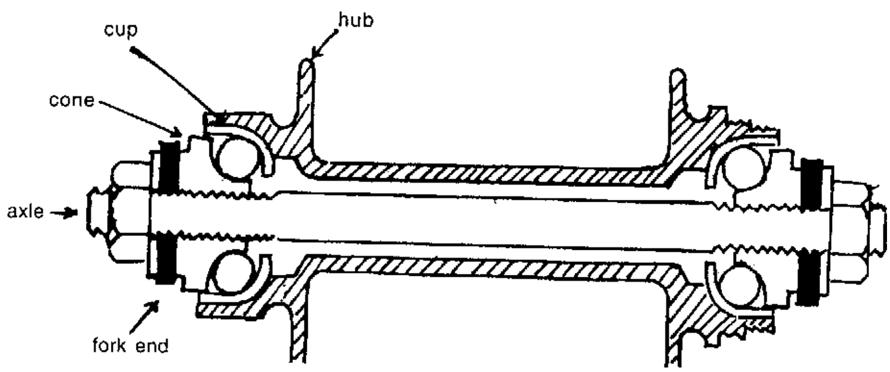
Racing cyclists who prefer speed over comfort use higher inflation pressures than others. The sink of the tyres (and hence their resistance to rolling also depends upon the total weight carried by the tyres which includes the weight of the rider, the bicycle and the tyres themselves. Besides cutting down on all other weights (including their own) the racers use specially designed tyres called the tubulars. These are made of silk or polyester fabric (impregnated with latex) and is sewn around a light-weight inner tube. The whole assembly is then glued on to the rim. Such tubular are very light, and high inflation pressures make them run very fast. But the decreased protection makes them much more puncture prone.

Bearings

The holes in a frame through which rotating shafts run are called bearings. In the early days of bicycles, the bearings needed constant lubrication and cleaning to keep the friction low. An improperly lubricated bearing resulted in (a) increased effort due to increased friction, and (b) heat built-up in the bearing itself because of the rubbing of the rotating shaft with the walls of the hole. The increased temperature often caused local melting of the walls and resulted in jamming-up of the wheels. Frequent cleaning of the bearings was recommended because the lubricating oil tended to catch the grit and dust which spoiled the bearing surfaces.



Schematic of a typical ball bearing in a bicycle. The shaft constitutes the hardened 'cone' and the frame has the 'cup'. The balls run between the cup and the cone.

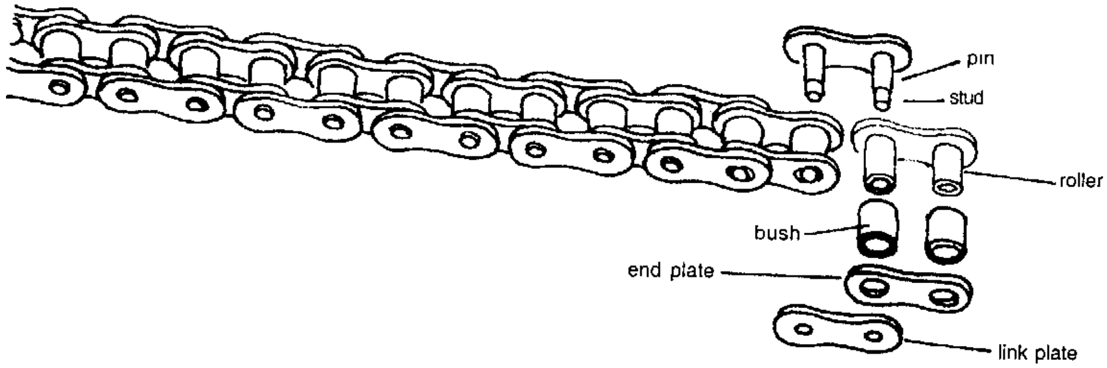


A section of the front hub bearing.

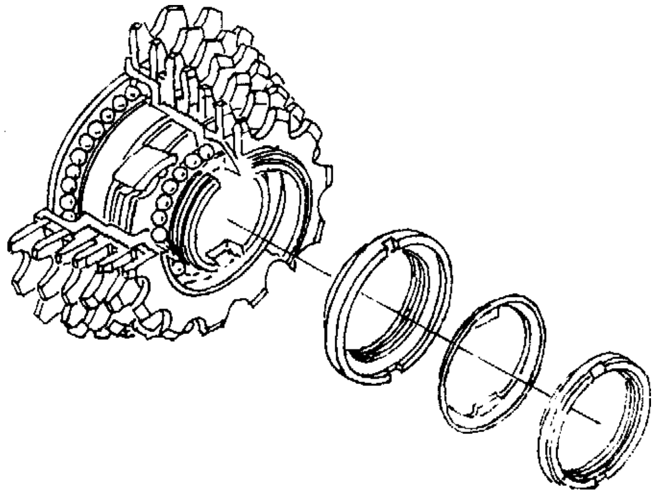
The introduction of ball and roller-bearings is an extension of the idea of the use of the wheel itself. A hardened roller running between two surfaces eliminates the relative sliding and reduces the resistance due to friction drastically. The typical design of a bicycle bearing consists of a row of balls rolling between an outer cup and an inner cone. The balls, cone and the cup, all are made of hardened steel to resist wear or deformation. The reduction in friction is so dramatic that these bearings are also known as the anti-friction bearings. Their life is fairly long, even without frequent oiling. Furthermore, these can be replaced easily and inexpensively, if necessary.

Chain

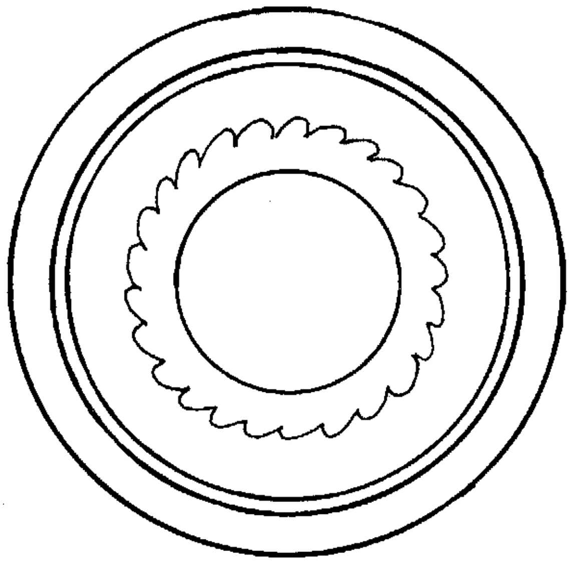
The design of chain also went through a process of evolution. The earliest chains were simple pin types in which the pins rolled directly on the sprocket teeth resulting in large rates of tooth wear. The latter designs introduced rollers and bushes so that neither the sprocket teeth, not the end plates bore and rolled on the pins directly, and thereby, increased their life immensely. The modern bush-roller chain, designed essentially in 1880, is so efficient and reliable and it is still used to drive the cam-shafts of automobile engines.



The bush-roller chain (1880) combines high efficiency, low weight and long life. Except for better materials and precision of manufacturing, the chains have not changed in one hundred years since their invention.



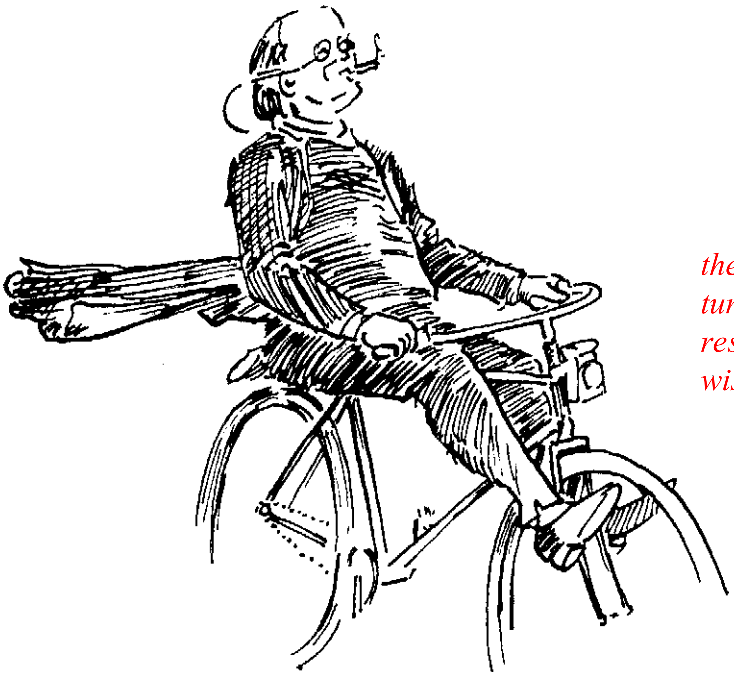
The details of a seven-speed hub. The chain runs on one or the other of sprockets which are screwed only to the freewheel. The internal ratcheted teeth are shown alongside. The spring-loaded pawls engage when the free-wheel rotates in one direction, and drives the hub and the wheel. The pawls are depressed when it rotates in the other direction, permitting slippage between free-wheel and the hub. Where are the pedals located relative to this free-wheel—to the left or to the right?



The essentials of a free-wheel. The ratchet like teeth engage with spring-loaded pawls when rotating in one-direction

Free Wheel

A free wheel is a device which connects the sprocket of the driven wheel to its hub in an ingenious manner. It engages the wheel to the sprocket when the sprocket rotates in the forward direction, but lets the wheel roll forward freely when the sprocket runs in the backward direction, or is not running at all. It is easy to see that such a device makes getting on and off a moving bicycle much easier than when the sprocket and wheels are attached without a free-wheel. This happens because without a free wheel the pedals must rotate constantly with the moving wheels. Similarly, coasting, which is the forward motion of a bicycle due to its inertia alone without pedalling, will not be possible without a free wheel.



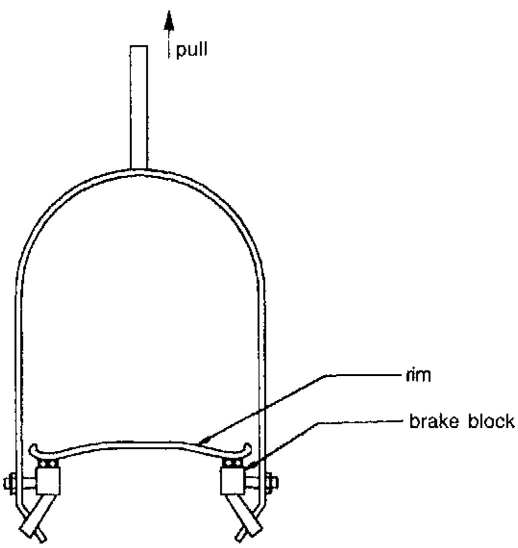
Before free-wheels were introduced, the riders sought relief from the ever-turning pedals through the use of foot rests — sine qua non for all who wished to ride with ease.

A free-wheel assembly has a number of spring-loaded blocks termed as pawls. Each pawl folds into a cavity in the shaft when it is pressed down, but pops out when the pressure is taken off. The corresponding sprocket has a number of ratchet-like teeth cut on the inside. When the sprocket rotates in the reverse direction, the pawls are pressed down by the sloping sides of ratchet teeth and let the sprocket roll on the shaft. But when the sprocket rolls in the forward direction, the pawls open out and are engaged against the straight sides of the ratchet teeth. This happens whenever the pedalling moves the sprocket faster than the wheel, so that the muscle power is fed into the wheel, accelerating it.

The free wheel, thus, allows coasting on a bike with one's feet on stationary pedals, or even pedalling backwards. The introduction of free wheels made the bicycle safe to get on and off, and one could coast down a hill without having to pedal constantly.

Brakes

There was no particular need for brakes until the time free wheels were introduced since the pedals moved with the wheel. One could brake the bicycle simply by attempting to rotate the pedals backwards. But this required a large amount of force, particularly if one was going fast. This made downhill bicycling a very hazardous sport. The earliest of the bicycle brakes consisted of just a metal spoon which was operated by a hand lever and was pressed against the rim of the front wheel. It was quite effective on a solid rubber tyre, but tended to play havoc with the air-filled ones.

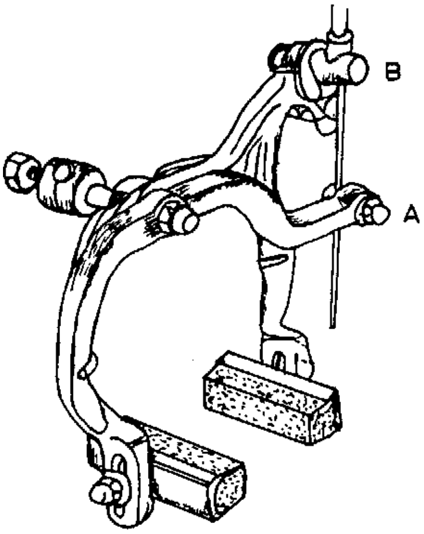


The stirrup brakes, still common in Indian bicycles, operate on the underside of the rim. The operating mechanism of these brakes is quite unreliable. These also need tar too frequent adjustments.

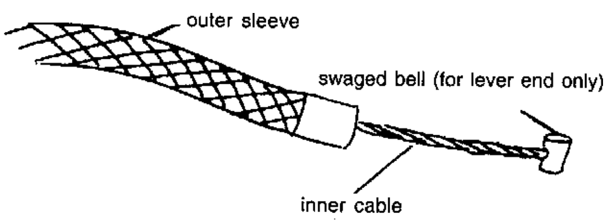
Soon after the introduction of pneumatic tyres the stirrup brake was developed. It is still used on many bicycles. It consists of a couple of rubber pads which were pressed against the underside of the rim. The force of friction between the pad and the rim acts on the rim to stop its rotation. This force of friction depends on the material of the pad and the pressure with which it is pressed against the rim. A large value of this pressure is obtained by using lever mechanisms that transmits the motion of the hand operated brake lever to the brake pads with a large value of mechanical advantage.

The stirrup brakes were soon replaced by calliper brakes in which the brake pads are pressed against the flat sides of the rim rather than on the underside. The main advantage of the calliper brakes lies in the fact that these brakes are not affected by the inevitable non-circularities of the rim. The stirrup brakes on the other hand lose contact with the rim at places where the rim is out of circle.

Also, the calliper brakes are not disturbed while changing tyres whereas the stirrups need to be moved out of the way.



*Calliper brakes operate against the sides of the rim. They are operated by the pull of the brake wire through &n outer casing. The outer sleeve is attached at **A** and the inner cable at **B**.*



The outer sleeve is attached to one arm of the callipers and the inner cable to the other. When the cable is pulled through the sleeve (through a similar arrangement at the brake lever end) the two arms of the calliper brakes are squeezed together against the sides of the wheel rim.

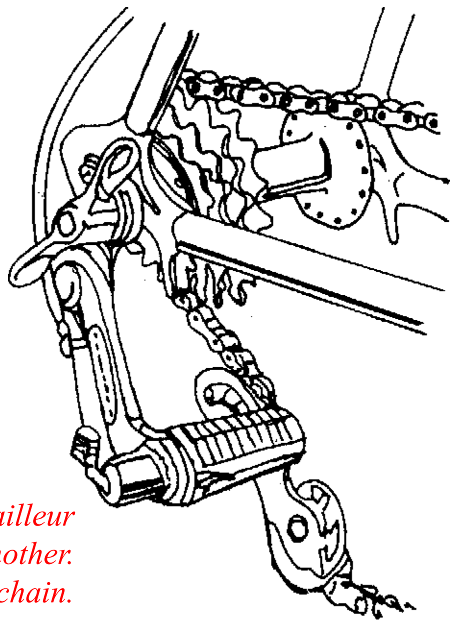
Calliper brakes are operated through a flexible cable which is made up of an inner-wire running through an outer-sleeve. The operation of the lever puts the inner wire in tension and the outer sleeve in compression. The tension and compression act on the two halves of the callipers closing the brake shoes against the rim.

The inner tension-cable running in an outer compression-sleeve is a most effective means of remote operation of a number of mechanisms. The gear-change of a bicycle or a motor cycle, the operation of a clutch or an accelerator of a motor bike is all operated by such a system. A variation of such a cable is also used for remote operation of rotating components. A car speedometer cable is an example of such a use.

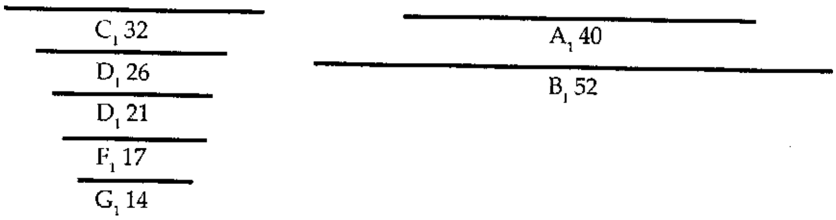
Gears

As long as the direct cranking of the front wheel was the method of moving a bike, the only method of increasing the distance travelled per revolution of the pedals, also known as the gear ratio, was to increase the size of the wheels, as was done in penny-farthings. A large gear ratio meant that the torque at the hub was much smaller than the effort torque applied on the pedals. This was alright as far as going on a level ground was concerned, but it made going uphill or accelerating quite difficult.

What was required was some way of changing the gear ratio at will: low for starting or going uphill, and high for travelling on level ground. This was not possible in a penny-farthing because the gear ratio was determined solely by the size of the front driven-wheel.

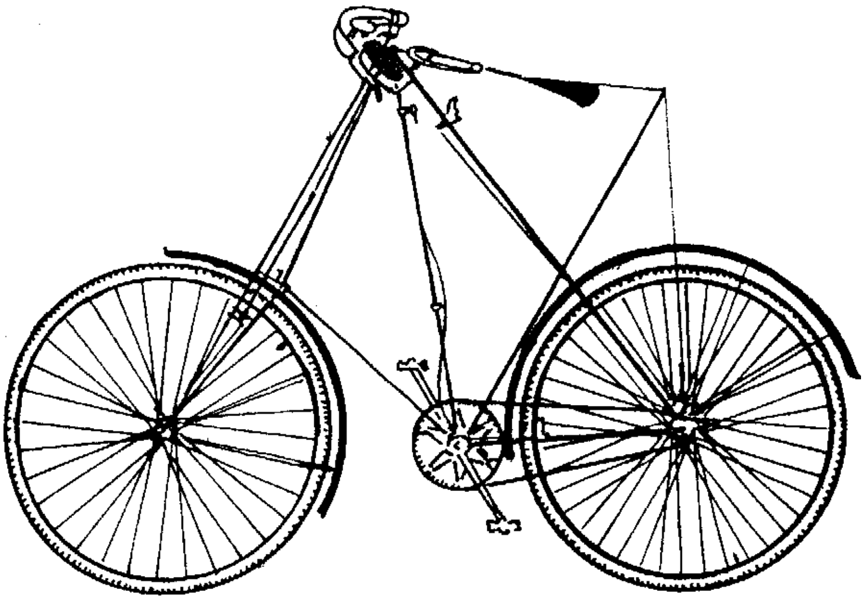


An inner-cable-through-outer-sleeve pulls the derailleur to a side, derailing the chain from one sprocket to another. The spring loaded idle roller takes up the slack of the chain.



Typical sprocket and chain wheel sizes (in number of teeth) in a ID-speed bike. The various combinations give gear ratios from a low of 34" (travel on ground in one rotation ot a 27" wheel) to a high of 100". Low gears are useful for uphill climb or acceleration. High gears are used for cruising or downhill runs.

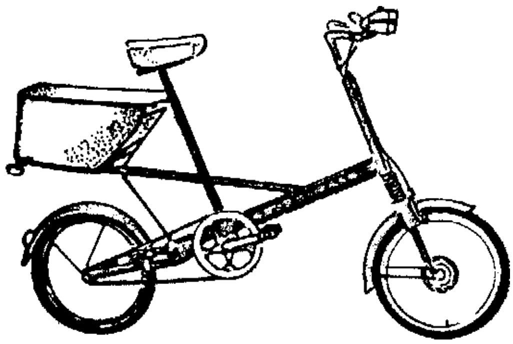
The chain-driven safety bicycle, however, permitted quick change of gear ratios. Various mechanisms have been suggested for changing gears, but the one that is increasingly used these days consists of a number of sprocket wheels of different diameters at the rear wheel. When the chain runs on a larger diameter sprocket, the gear ratio is lower than when it runs on a smaller diameter sprocket. The slack of the chain resulting because of the change in the diameter of the sprocket is taken up by a spring-loaded pulley mechanism known as a derailleur. As the gear-change lever is shifted it actuates a cable. The cable pulls the derailleur mechanism to one side, making the chain 'derail' from one sprocket to another. This arrangement is fairly light and efficient, but requires careful adjustments. The hub in a derailleur may have three or five sprockets, giving three or five 'gear ratios' or speeds. The ten-speed bikes have a similar mechanism at the hub and, in addition, two sizes of chain-wheels at the pedals. The combination of a two-speed chain wheel and a five-speed hub gives the 10-speed bicycle commonly used by sportsmen.



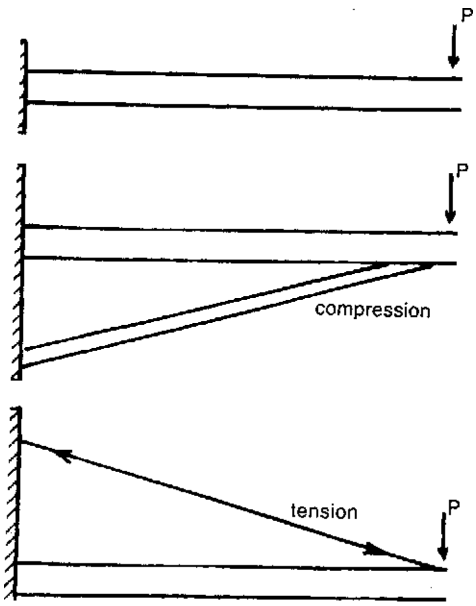
Dudley-Pederson first appeared in 1907. It had the lightest frame ever, because of the full triangulation. Hammock seat was a particularly appreciated feature. These are being reissued by a Danish firm.

Frames

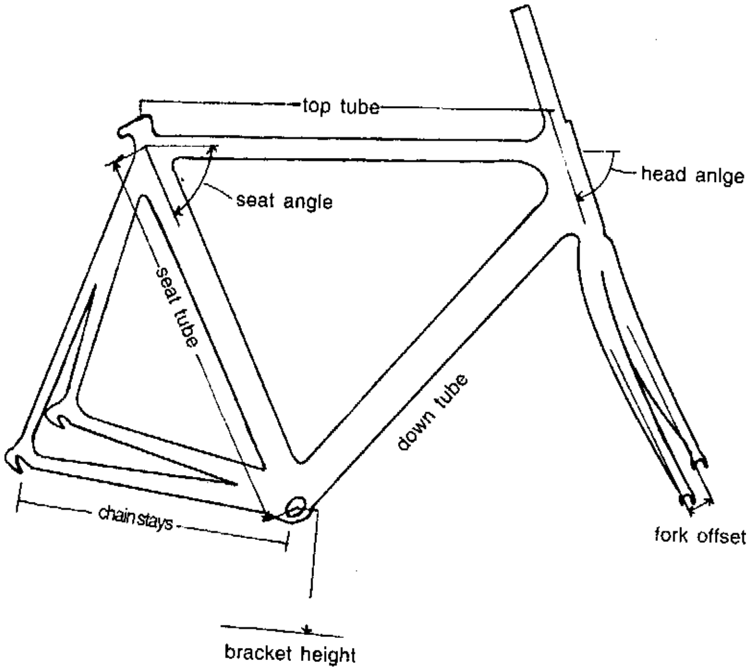
The frames of bicycles have shown much development over the years. The modern tubular diamond frame is quite far removed from the crude wooden planks of the original hobby horse. A modern frame is strong and yet light. This economy of design is obtained by exploiting the fact that a structural member is weakest when it supports a load which tends to bend it. If this member is propped up from below, the load is carried in compression, and much more load can be carried. A still better arrangement is the one when the member is strengthened by a cable which takes the load in tension. Thus, the lightest structure results when its components support loads in tension or in compression, but not in bending. Such a structure consists of a series of triangles. Tower cranes, roof trusses and steel bridges all use this triangulated construction. The diamond frame of a modern safety bicycle is also triangulated to a large extent. The ultimate in frame triangulation is seen in a 1907 Dwaley-Pederson. It was so light that the total frame weighed only 6.4 kgs.



Moulton bicycle has a cross frame which is simpler but not as strong as a triangulated frame. The convenience of an open frame is a trade-off for higher weight.



The top member resists load by bending. The bending is reduced in the other arrangement, resulting in much more efficient structures.



The classical diamond frame is well triangulated and quite efficient. This has been the standard frame for the last 100 years, except for the famous Moulton frame, which is net as strong, but gives other advantages.

Diamond frames were introduced in 1887, and since then almost all bicycles have had such frames. A notable exception is the Moulton bicycle introduced in 1964 which uses an X-frame construction. This frame is definitely heavier than a diamond construction but other advantages, such as the fact that it is suitable for skirt-wearing women as well, make this acceptable.

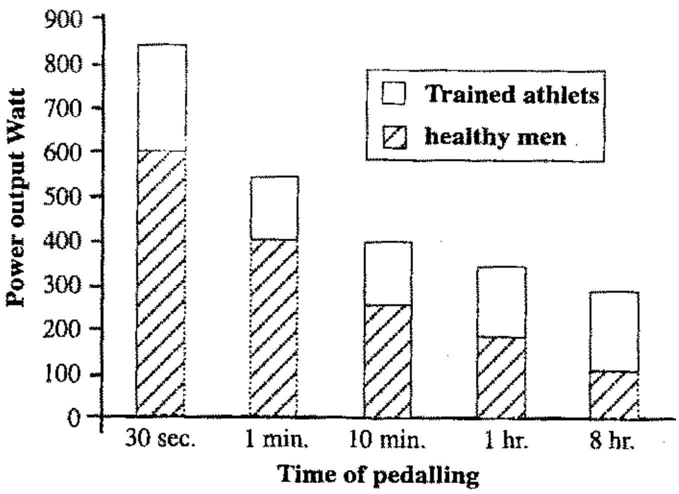
Another weight saving device is the use of hollow tubes as main-frame members. A bamboo exhibits the excellent properties of the hollow circular tubes. It takes up to twice as much load as any wooden beam of equal weight.

The Science of Bicycle

Force and Power

The first consideration in the design of any vehicle is the calculation of force and power. Whenever a body moves or rolls over a surface some forces come into play which tend to oppose the motion. We, therefore, need to apply a force to overcome these resisting forces. Acceleration of a body needs an additional force. Larger the weight of a body or larger its acceleration, larger is the force required. Therefore, racing bicyclists who need to accelerate fast, attempt three things:

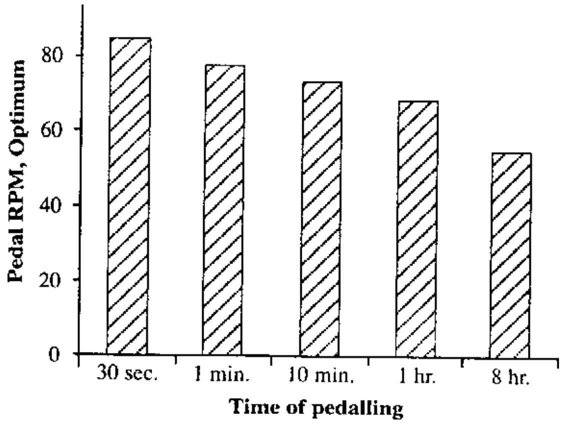
- keep the resistance low,
- keep the weight small,
- apply as large a force as possible.



Effect of duration on the pedalling power output. The graph shows that the power output level in short bursts could be up to six times that in long runs. Comfortable level for routine bicycling is taken at 60 W.

Similarly, going uphill requires a larger force because the weight of the body has to be hauled up the hill. We have learnt that a large force is applied by changing to a low gear. That is one reason why we start in a low gear, and shift up when we have built up speed and do not need to accelerate further. Similarly, going uphill requires low gears.

Power refers to the rate of energy consumption in motion. It depends upon the force of resistance and the speed of motion. Larger the force or the speed more is the requirement of power. In pedalling a bicycle, the power for motion comes from the human engine through its muscles. Muscles are like fuel cells, converting the chemical energy in food into mechanical energy at the crank. The speed of the bicycle is limited to a large extent by the capacity of power delivery by the muscles.



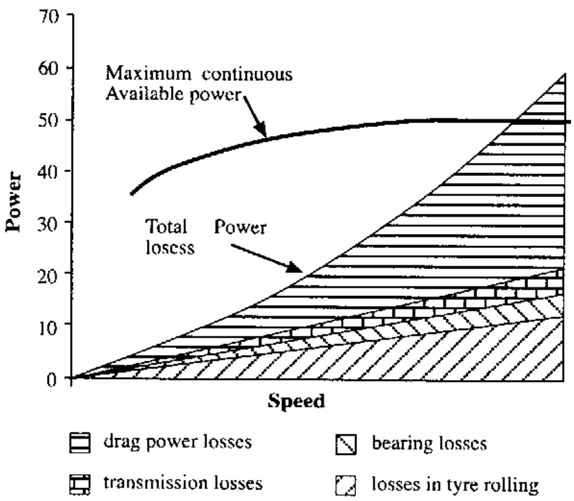
The maximum power is obtained at an optimum pedalling RPM which decreases with the duration of pedalling. A rate of 50 RPM is recommended for 'healthy males' for routine bicycling. Racers are known to go up to 150 RPM in very short bursts (up to 5 seconds).

The functioning of our bodies is quite complex. One can obtain really high bursts of power if one goes only for a short duration. But the level of power output sustained over a long time is much lower than this. Thus, the speed on shorter runs is far larger than the speed during long endurance runs. Chart below shows the rapid decline of the power output with duration. A comfortable level of power output on a sustained basis for an 'average' bicyclist is usually taken as 50 W.

Power Audit

Let us account for the power spent in bicycling. When a bicyclist starts from rest, the power that he spends goes into overcoming the various frictional resistances and in providing the kinetic energy increase associated with his acceleration. When he pedals uphill, a part of the power is also spent in increasing his potential energy because of his increased altitude.

Let us first consider a level steady run at constant speed. All the power delivered by the rider now goes to overcome the various resistances. The most significant loss occurs in the tyre rolling resistance. Typical resistance force is about 4 Newton, which at a speed of 18 km/h (or 5 m/sec) consumes 20 W. This power increases proportionately with speed, that is, when the speed is doubled, the power is doubled too.

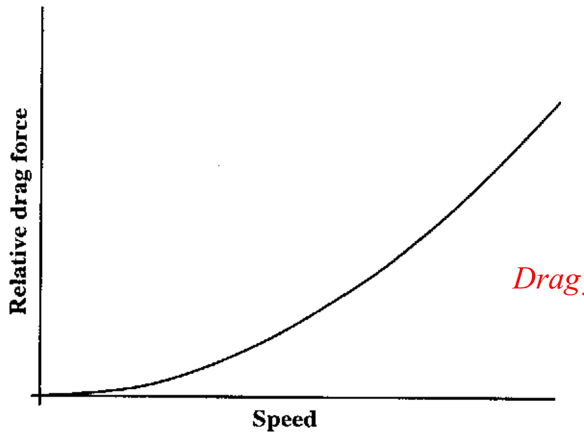


In the region where the available power is more than the power loss, the difference goes to increase the kinetic energy of the bicycle and the rider. The maximum speed is reached when the total power losses consume all the available power.

The energy losses in the various ball bearings are very small and are estimated at less than 1 W. The transmission chain with all its rubbing amongst various links and between links and the sprockets consumes more power—up to 3 W. The total so far accounts for only 24 W or about one-half of the input power. Where does the rest go? Let us find out.

Wind Resistance

All bodies when moving through air experience a resisting force termed as drag. One feels this force when walking against the wind. For speeds commonly encountered in bicycling, this resistance force varies as the square of the speed. Thus, as the speed is increased by a factor of 2, the drag force increases by a factor of 4, and the power consumed (which is the four times the speed) by a factor of 8. This is really a steep increase, and does, in effect, determine the maximum speed for a given effort.



Drag force varies as square of the speed.

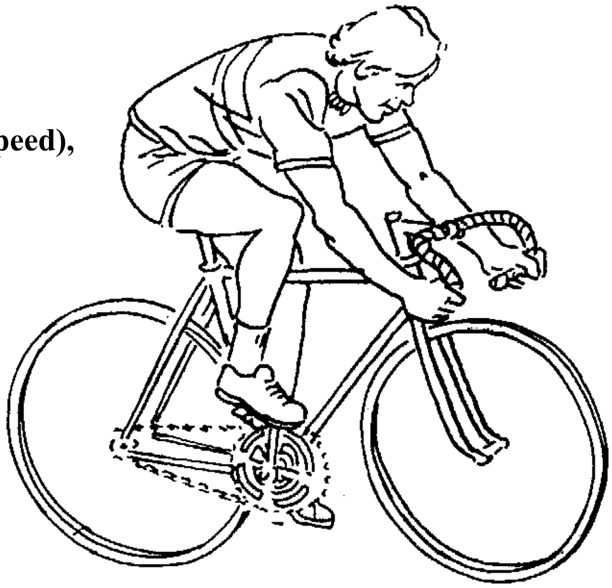
A survey of literature shows that a person riding an ordinary bike in the usual upright position experiences a drag which is given by the following approximate formula

Drag force (in Newton) = 0.015 x (speed) x (speed),

and the power consumed in given by

Drag power (in Watt) = **0.004 x (speed) x (speed) x (speed),**

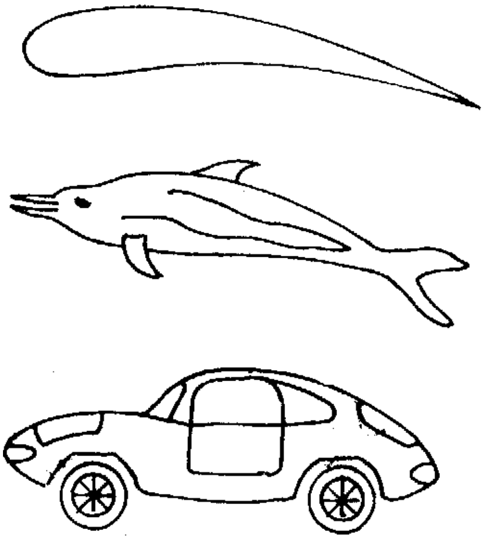
where speed in measured in kilometers per hour.



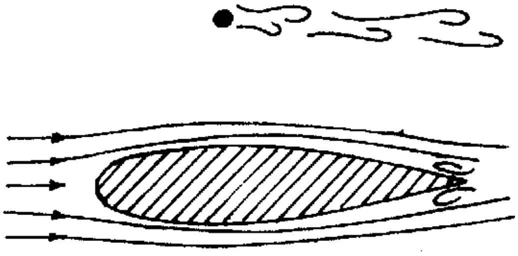
Reducing frontal area by crouching is one way to reduce the drag and increase speeds.

Thus the power required to overcome the drag, which is only 0.5 W at 5 km/h, blows up to 4 W at 10 km/h, and up to 13.5 at 15 km/h. At 18 km/h the drag losses are 23.3 W, almost equal to all other losses put together.

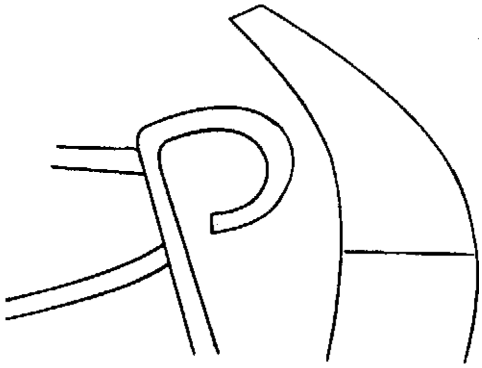
It should be noted that the above formulae are valid for pedalling through still air only. The drag is determined by the speed of the body relative to the air, so that with a head wind of 5 km/h, one would encounter the same losses at a speed which is 5 km/h less than the speed in still air. It should be clear by now that the maximum speed is essentially limited by the air drag. One must strive to reduce the drag as much as possible in order to increase the speed. Our experience with designs of high speed cars and aeroplanes has shown that the drag force depends on the 'frontal' area of the body and on the contours of the body (besides the all important speed, of course). Thus, a racing bicyclist crouches on dropped handlebar to reduce the counter wind flow. A bicyclist lying prone would offer still less area and some modern bicycles have been designed to exploit this. Further reduction in the frontal area can be achieved by changing into tight fitting clothes as the racers do.



Drag is reduced by streamlining the body shape, as for an aerofoil, a dolphin and a high performance car.

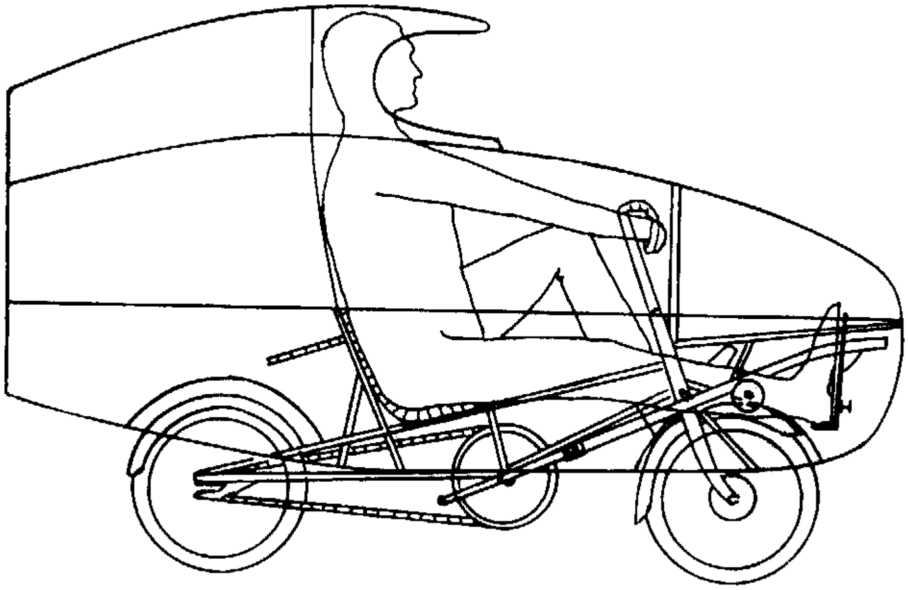


The aerofoil shape and the cylindrical wire of one-tenth frontal area have the same drag.



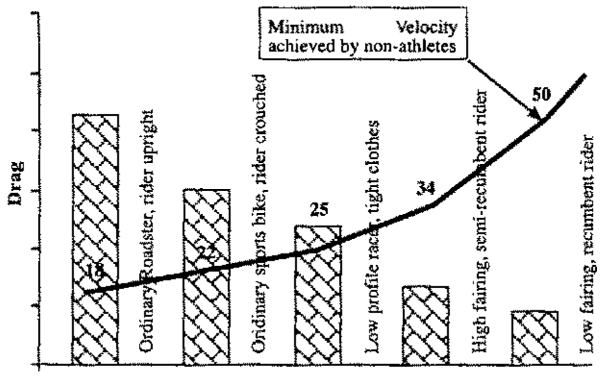
A fairing on the handle bar results in partial streamlining. Lowered draw can increase the maximum speeds by as much as 10 percent.

The contours of the body are an important determinant of the drag. Notice the smooth shapes of the racing cars in contrast to the lines of the earlier touring cars. Notice also the tear-drop profile of a dolphin which has been copied by the designers of aeroplanes. Such 'streamlined' shapes and reduce drag. If a long tapering tail is attached to a sphere, one can reduce the drag power requirements by a factor of hundred.



An aerodynamically shaped shell around the bicycle can reduce the drag drastically. The recumbent position of the rider reduces the frontal area, lowering the draw further.

How can this information be used in the design of a bicycle? Not easily. The human profile is far from streamlined. But if we enclose the bike and rider in a tear- drop shell we can take advantage of the reduced drag. Some attempts have been made recently (with the rider in the recumbent position to reduce to frontal area) with great success as far as the maximum attainable speeds are concerned. But the handling qualities of such vehicles to date make them fit for little else but breaking speed and endurance records on tracks.

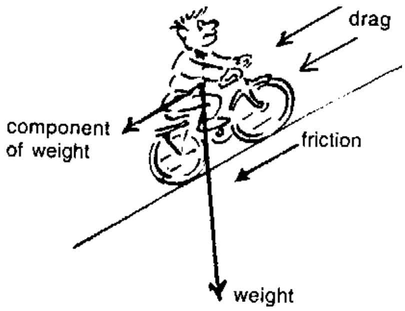


Relative magnitude of drag for various bicycle shapes and riding positions. The numbers represent the approximate maximum speeds attained by non-athletic males in continuous rides. The increase in speeds is largely due to reduced drag.

Pedalling Uphill

When a rider pedals uphill, he raises his bicycle and his own weight and therefore has to apply a larger force at the hub than when he is only overcoming the resistance. This makes going uphill very difficult, unless the rider has a geared bike and can change down to a lower gear ratio giving him a larger mechanical advantage (though a reduced velocity ratio). Thus he goes slower but easier.

In the energy audit, we now have an additional term. The rider's potential energy increases as he goes up, and this energy must also be supplied by the muscles. This reduces the power available for overcoming the resistance, and he may not be able to go as fast as on the level ground.

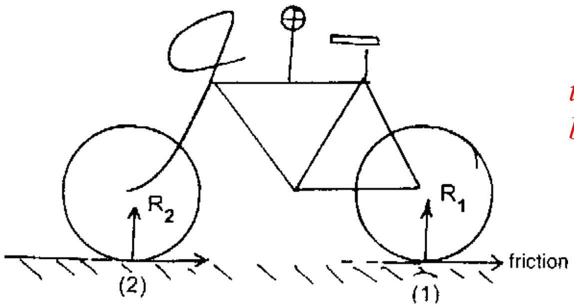


While going uphill, the pedalling force must overcome the drag, the Motional force, as well as a component of the weight.

The fact that air-drag consumes a fair amount of power, and depends upon the relative speed of the body with respect to air, leads to an interesting situation. Under certain conditions, it might be easier to climb a hill than go down it. This happens when we have a wind uphill. This may assist the climb to such an extent that saving in drag power may offset the increased cost to potential energy increases. On the other hand, increased power consumption to overcome the drag in a head-on wind may be more than the recovery of potential energy in a down-hill run.

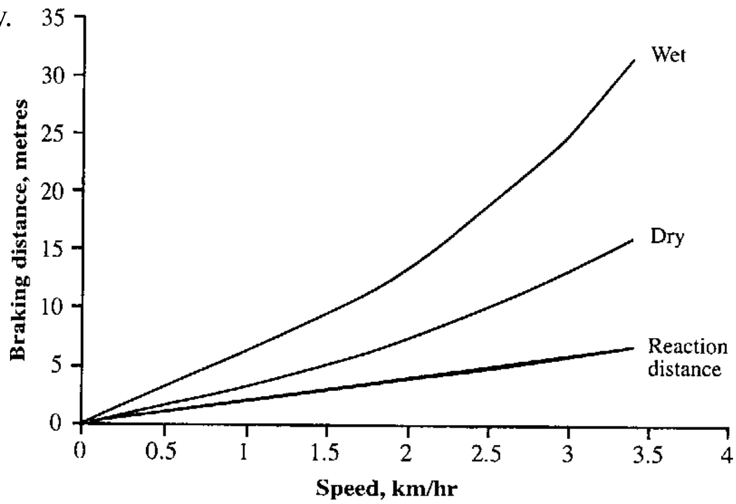
Braking

A bicycle is braked by jamming pads of friction material (usually rubber) against the inside or the sides of the rim. This restrains the wheel from turning, and consequently the tyre drags on the ground instead of rolling on it. It was seen before that the friction during sliding could be up to 100 times that in rolling and this force between the ground and the sliding wheel is what slows down and finally brings the bicycle to rest.



The frictional force at the road tends to 'swing' the bicycle pivoting about point (2). Front wheel brakes should be applied with caution.

One has to be careful while applying the brakes. If the full braking force is applied and both wheels are locked, the large friction force at the ground can produce a torque which can swing the bicycle with the rider over the front wheel. It is recommended not to apply the front wheel brakes fully before the bicycle has slowed down appreciably, except during an emergency.

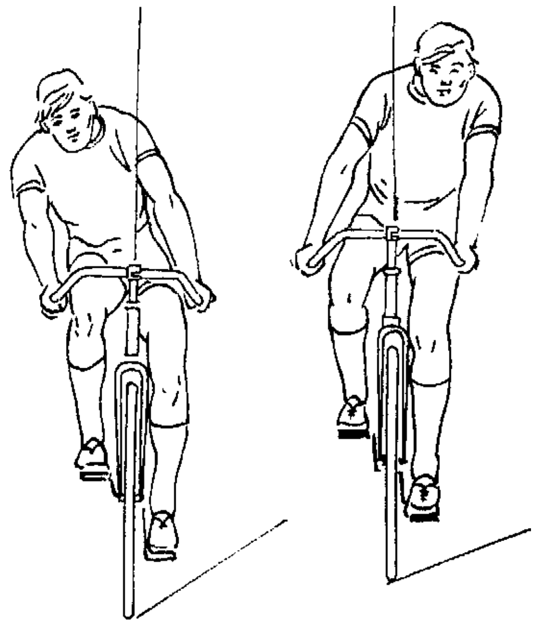


The total braking distance in wet conditions is much larger than in dry. Extreme caution is called for in riding when it rains.

The bicycle brakes are very unreliable in wet weather. When the brake pads are wet, the coefficient of friction between the pads and the rim decreases drastically and it becomes difficult to bring a wet bicycle to stop in a hurry. Some internal hub brakes have been developed which protect the brakes from water, but they are either too expensive or heavy to for common use.

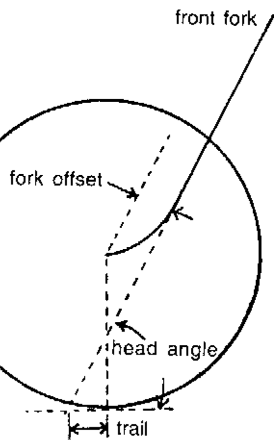
Stability

For a kid and an adult alike, there is no experience more thrilling than 'hands-off bicycling. Even with hands on, it seems miraculous that a vehicle with only two wheels can stay upright over rough roads.



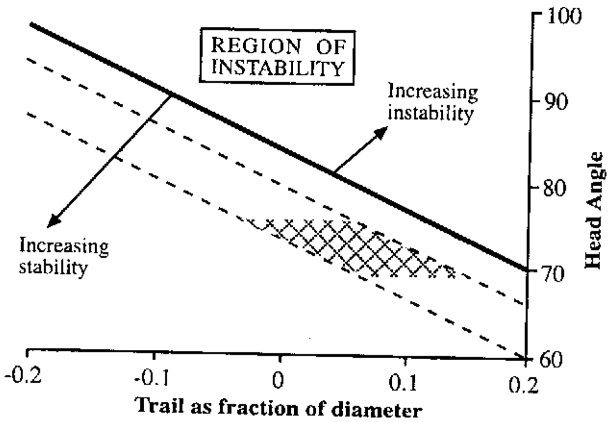
If the bicycle leans to the left, the rider leans further to the left; the wheel turns to the left and the bicycle uprights. A rider learns to do this automatically.

Any rider knows that a bicycle is balanced by steering into a fall just like a juggler balances a broom on his finger. If a bicycle begins to fall to the left, the front wheel is turned to the left, and this makes the bicycle upright again. But one has to do it consciously only when one is learning to ride. As the rider gains confidence, he relaxes, and the bicycle seems to do the correction by itself—as it indeed docs when one rides with both hands-off the handle bar. How does a bicycle straighten itself when it begins to fall?



Front fork geometry. The variables that affect the stability of the bicycle.

It is a complex question, made more difficult because of the complex geometry of the steering head. It has been shown that a bicycle rights itself because of the complex interplay of the inclination of the steering tube (termed as the steering head angle), the bent of the front fork (resulting as the steering head angle), and the lean of the bicycle frame from the vertical. For certain combinations of head angles and fork offset the steering automatically turns into the lean. The reason for this automatic turning is that under these conditions the net frame height decreases as the steering turns into the lean and as we know the natural tendency of a body is to keep the height of its centre of gravity at the minimum.



A bicycle should be stable but not too stable. Most practical bikes have parameters that are in the cross-hatched region. The head angle is restricted by the clearance between wheel and the pedals and the ease ot handling the bar steering.

This property of a bicycle to stay erect while running is termed as stability. We can increase the stability of a bicycle by increasing the head angle or by decreasing the offset—even making it negative. But stability is not all. One could make a bicycle so stable that it becomes hard to steer into a curve of one's choice. Such a bicycle would naturally follow the contours of the road rather than go where one wants it to go. It is for this reason that there is only a small range of practically useful head angles (between 72°-74° and of fork offset (between 6 to 8 percent of the wheel diameter). Lesser offset would mean a more stable bicycle, but one which would require larger forces to steer.

Bicycle—a Machine Tailored to the Human Body

Due to the use of ingenious mechanisms and devices and the principles of physics, the bicycle has evolved into its present shape. But a bicycle is more than the sum of its component parts. The high efficiency of a bicycle is only partly due to its low weight, the reduced friction because of the ball bearings and bush-roller chains minimum rolling resistance due to pneumatic tyres. The main reason for its high efficiency is the way the machine is fitted to the human body.

Unlike a man walking or running, a cyclist's legs do not support his weight. The important leg muscles are now concerned only with motion and not with keeping the torso upright. Peddling uses his thigh muscles which are the most powerful ones in his body. During walking, the whole body oscillates in a vertical plane which dissipates work. But during bicycling the torso is stationary, the feet go in smooth circular motion and only the thighs are bobbing up and down. The geometry of the frame is such that the legs bear directly on to the pedals utilizing the applied muscular force to the maximum. The handle-bar and the saddle are so located (or can be so adjusted) that the arms are nearly straight, supporting the body somewhat but without undue strain. The racing posture is a little less comfortable but a racer is a different breed altogether—preferring performance to comfort.

Some Interesting Websites

www.exploratorium.edu/cycling

A good resource on various aspects of bicycling. This site also contains exceptionally good introduction to the science and arts of many sports. Highly recommended.

www.science.uva.nl/research/amstel/bicycle
Scientific and cultural aspects of the bicycle. An important learning resource.

www.pedalinghistory.com
A very good resource for various aspects of bicycling, as sport and as a movement.

www.bicyclepaintings.com
A collection of fine oil paintings of historical bicycles.

www.state.il.us/kids/isp/bikes/default.htm
Preparing to ride? Tips and rules.

www.ctuc.asn.au/bicycles
Site of the Canberra Bicycle Museum and Resource Centre.

www.cycling.org/lists/hardcore-bicycle-science
A good description of bicycle science

www.ibike.org/historymuseum.htm
Website of the International bicycle fund

www.bicyclemuseum.com
Home page of the Bicycle Museum of America

Time Line in the History of Bicycle

1791 The first reported plank-with-two wheel on which the rider sat and propelled by thrusting feet on ground.

1817 Baron von Drais makes the front wheel steerable. Hobbyhorse is invented. Huge success as a novelty.

1839 Kirkpatric MacMillan of Scotland attaches treadle and cranks to the rear wheels to "invent' the first two-wheeled vehicle. Not well received at all. MacMillan is credited now to be the inventor of the bicycle.

1863 Pedals are added to the front wheel. The Bone-shaker is launched. Riding velocipedes soon becomes a fad.

1865 Radial (and torsion) spokes are introduced making bicycles lighter.

1869 Solid rubber tires are introduced in place of iron tires. The term "bicycle' is first used.

1870 Tangential spokes are used replacing radial and torsion spokes. No major change since then.

1872 Tall-ordinary or the Penny-Far thing makes appearance in England.

1888 JK Starley invents the Rover safety bicycle.

1889 Pneumatic tires are first used. The development of the basic bicycle is complete.

1896 Coaster brakes invented.

1899 Mile-a-minute barrier broken. Murphy completes a mile in 57,75 second.

1903 Bicycle mechanics Orville and Wilbur Wright Invent' the aeroplane.

1965 Conservation movement and physical fitness buffs recognize the importance of bicycle and a bicycle boom begins.

1972 For the first time ever, bicycles outsell cars in United States of America.

1980 Disc wheels introduced in competition bicycles to reduce the aerodynamics drags due to individual spokes.

1985 Bicycle speed exceeds 150 miles per hour. John Howard sets the speed record at 152.28 mph.

END