Pascal next reasoned that if the weight of the air is really the force, then at the summit of a high mountain it is weakened, and the column would be lower. He accordingly carried his apparatus to the top of a tower, and finding a slight fall in the mercury, he asked his brother-in-law, Perrier, who lived near Puy de Dôme, a mountain in Southern France, to test the conclusion. On trial, it was found that the mercury fell 3 inches. "A result," wrote Perrier, "which ravished us with admiration and astonishment." Thus was discovered the germ of our modern barometer, and the dogma of the philosophers soon gave place to the law of gravitation and our present views concerning the atmosphere.

Consult Pepper's "Cyclopedic Science"; Bert's "Atmospheric Pressure and Life," in "Popular Science Monthly," Vol. XI., p. 316; "Appleton's Cyclopedia," Articles on Hydromechanics, Atmosphere, Pneumatics, etc.; Delaunay, "Mécanique Rationelle"; Boutan et D'Almeida, "Cours de Physique"; Müller, "Lehrbuch der Physik und Meteorologie."

On the theory of Wave-motion, and the subjects of Sound and Light, which are now to follow, consult Lockyer's "Studies in Spectrum Analysis"; Lloyd's "Wave Theory"; Taylor's "Science of Music"; Blaserna's "Theory of Sound in Relation to Music"; Tyndall's "Sound" and "Light"; Lockyer's "Water-waves and Sound-waves" in "Popular Science Monthly," Vol. XIII., p. 166; Shaw's "How Sound and Words are Produced," in "Popular Science Monthly," Vol. XIII., p. 43; Mayer on "Sound"; Schellen's "Spectrum Analysis"; Airy's "Optics"; Lockyer's "Spectroscope"; Chevreul's "Colors"; Spottiswoode's "Polarization of Light"; Lömmel's "Nature of Light"; Helmholtz's "Popular Lectures on Scientific Subjects"; "Appleton's Cyclopedia," Articles on Sound, Light, Spectrum, Spectrum Analysis, Spectacles, Heat, etc.; Stokes' "Absorption and Colors," and Forbes' "Radiation," in "Science Lectures at South Kensington," Vol. I.; Mayer and Barnard's "Light"; Draper's "Popular Exposition of some Scientific Experiments," in "Harper's Magazine" for 1877; Core's "Modern Discoveries in Sound," in Manchester Science Lectures, '77-8; Dolbear's "Art of Projecting"; Draper's "Scientific Memoirs"; Steele's "Physiology," Section on Sight, pp. 187-196.

VI.

ON SOUND.

"SCIENCE ought to teach us to see the invisible as well as the visible in nature: to picture to our mind's eye those operations that entirely elude the eye of the body; to look at the very atoms of matter, in motion and in rest, and to follow them forth into the world of the senses."—TYNDALL.

ANALYSIS OF SOUND.

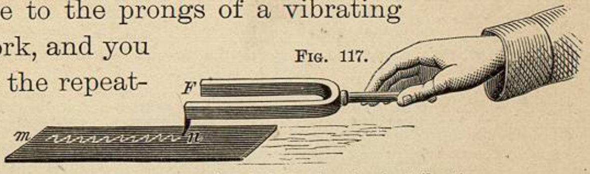
ACOUSTICS, OR THE SCIENCE OF SOUND.

1. Production of Sound.
2. Transmission of Sound.
   - (1.) Through Air.
   - (2.) In a Vacuum.
   - (3.) In Liquids.
   - (4.) In Solids.
   - (5.) Production of Motion by Sound.
   - (6.) Co-vibration through Air as a Medium.
   - (7.) Velocity of Transmission.
   - (8.) Loudness of Sound.
3. Refraction of Sound.
4. Reflection of Sound.
   - (1.) Law of Reflection.
   - (2.) Echoes.
   - (3.) Decrease by Reflection.
   - (4.) Acoustic Clouds.
5. Musical Sounds.
   - (1.) Difference between Noise and Music
   - (2.) Pitch.
   - (3.) The Siren.
   - (4.) Wave-lengths.
   - (5.) Tones in Unison.
6. Interference of Sound.
7. Vibration of Cords.
   - (1.) The Sonometer.
   - (2.) Laws of Vibration.
   - (3.) Nodes.
   - (4.) Acoustic Figures.
   - (5.) Harmonics.
   - (6.) Nodes of a Bell.
   - (7.) Nodes of a Sounding-board.
   - (8.) Musical Scale.
8. Vibration of Columns of Air.
9. Wind Instruments.
10. Co-vibration.
    - (1.) Sensitive Flames.
    - (2.) Singing Flames.
11. The Phonograph.
12. The Ear.
    - (1.) Range of the Ear.
    - (2.) Ability to Analyze Sound.

ACOUSTICS, OR THE SCIENCE OF SOUND.*

1. Production of Sound.—By lightly tapping a glass fruit-dish, we can throw the sides into motion visible to the eye.—Fill a goblet half-full of water, and rub a wet finger lightly around the upper edge of the glass. The sides will vibrate, and cause tiny waves to ripple the surface of the water.—Hold a card close to the prongs of a vibrating tuning-fork, and you can hear the repeated taps. Place the cheek near them, and you will feel the little puffs of wind. Insert the handle between your teeth, and you will experience the indescribable thrill of the swinging metal. The

Fig. 117.



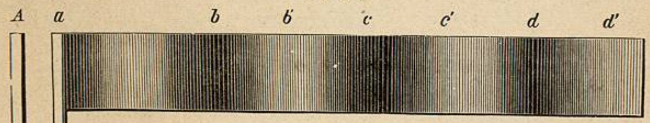
Tuning-fork Registering its Vibrations.

* The term *sound* is used in two senses—the *subjective* (which has reference to our mind) and the *objective* (which refers to the objects around us). (1.) Sound is the sensation produced upon the organ of hearing by vibrations in matter. In this use of the word there can be no sound where there is no ear to catch the vibrations.—An oak falls in the forest, and if there is no ear to hear it there is no noise, and the old tree drops quietly to its resting-place.—Niagara's flood poured over its rocky precipice for ages, but fell silently to the ground. There were the vibrations of earth and air, but there was no ear to receive them and translate them into sound. When the first foot trod the primeval solitude, and the ear felt the pulsations from the torrent, then the roaring cataract found a voice and broke its lasting silence. (2.) Sound consists of those vibrations of matter

tuning-fork may be made to draw the outline of its vibrations upon a smoked glass. Fasten upon one prong a sharp point, and drawing the fork along, a sinuous line will show the width (amplitude) of the vibrations.

2. Transmission of Sound. (1.) THROUGH AIR. In order that any medium shall transmit sound, it must be elastic. Most known bodies possess some elasticity, and hence sound may be transmitted through gases, liquids, and solids. The prong of a tuning-fork advances, condensing the elastic air in front of it. This transmits the compression to the air next forward, while the fork swings backward, leaving a rarefaction next to the compression. This

FIG. 118.



Sound-waves.

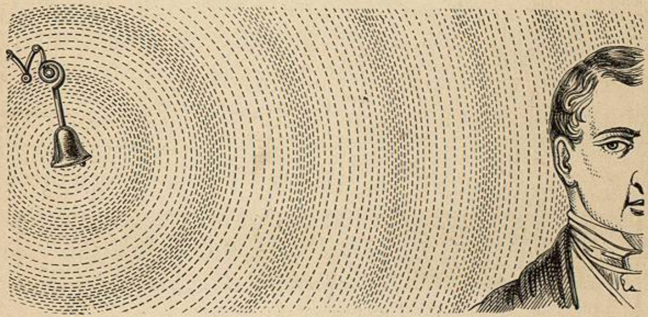
in turn advances, on account of the elasticity of the air, and is followed by a compression due to the second forward swing of the fork. This process is repeated, until the fork comes to rest, and the sound ceases. Each vibration produces a *sound-wave* of air, which contains one condensation and one rarefaction. In water, we measure a wave-

capable of producing a sensation upon the organ of hearing. In this use of the word there can be a sound in the absence of the ear. An object falls and the vibrations are produced, though there may be no organ of hearing to receive an impression from them. This is the sense in which the term sound is used in Physics.

length from crest to crest; in air, from condensation to condensation. The condensation of the sound-wave corresponds to the crest, and the rarefaction of the sound-wave to the hollow of the water-wave. In Fig. 118, the dark spaces *a*, *b*, *c*, *d* represent the condensations, and *a'*, *b'*, *c'* the rarefactions; the wave-lengths are the distances *ab*, *bc*, *cd*.

If we fire a gun, the gases which are produced expand suddenly and force the air outward in every

FIG. 119.

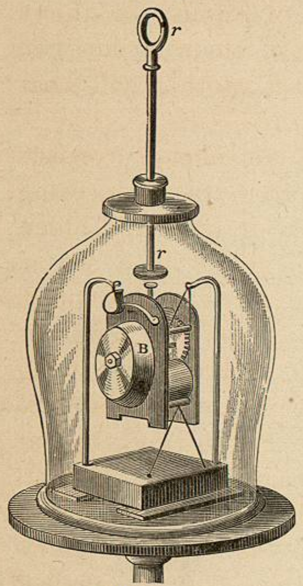


Propagation of Sound.

direction. This hollow shell of condensed air imparts its motion to the next one, while it springs back by its elasticity and becomes rarefied. The second shell rushes forward with the motion received, then bounds back and becomes rarefied. Thus each shell of air takes up the motion and imparts it to the next. The wave, consisting of a condensation and a rarefaction, proceeds onward. It is, however, as in water-waves, a movement of the *form* only, while the particles vibrate but a short distance to and fro.

The molecules in water-waves oscillate *vertically;* those in sound-waves *horizontally*, or parallel to the line of motion.*

Fig. 120.



Bell in Vacuum.

If a bell be rung, the adjacent air is set in motion; thence, by a series of condensations and rarefactions, the vibrations are conveyed to the ear.†

(2.) In a Vacuum. The bell *B* (Fig. 120) may be set in motion by the sliding-rod *r*. The apparatus is suspended by silk cords, that no vibration may be conducted through the pump. If the air be exhausted, the sound will become so faint that it can not be heard, except when the ear is placed close to the receiver.‡

In very elevated regions sounds are diminished in loudness, and it is difficult

* A continuous blast of air produces no sound. The rush of the grand aërial rivers above us we never hear. They flow on in the upper regions ceaselessly but silently. Let, however, the great billows strike a tree and wrench it from the ground, and we can hear the secondary, shorter waves which set out from the struggling limbs and the tossing leaves.

† "It is marvelous," says Youmans, "how slight an impulse throws a vast amount of air into motion. We can easily hear the song of a bird 500 feet above us. For its melody to reach us it must have filled with wave-pulsations a sphere of air 1,000 feet in diameter, or set in motion eighteen tons of the atmosphere."

‡ There would be perfect silence in a perfect vacuum. No sound is transmitted to the earth from the regions of space. The movements of the heavenly bodies are noiseless.

to carry on a conversation. The reverse takes place in deep mines and diving-bells.

(3.) In Liquids. Let two persons immerse themselves in water at a distance of twenty or thirty yards from one another. If one of them strikes two pebbles together, or rings a bell, the other will hear the sound with the utmost clearness.

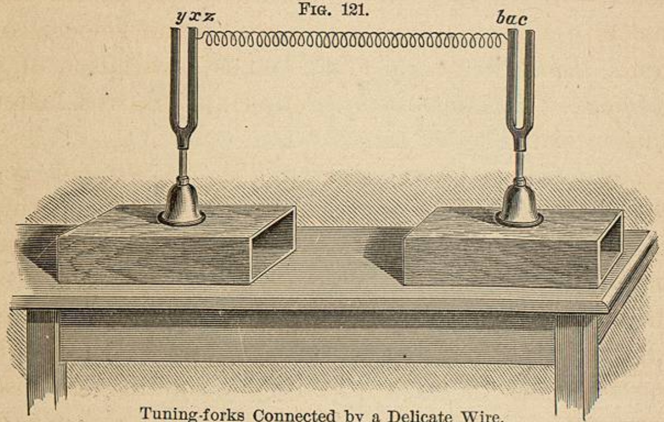
(4.) In Solids. The "Lovers' Telephone" consists of a pair of little cups, the bottom of each being made of an elastic substance, like stretched bladder, and connected with that of the other by a string. By stretching the string elastic force is developed, and on talking into one of the cups the sound is readily heard at the other. On relaxing the string and thus diminishing the elasticity, sound ceases to be conveyed perceptibly by it. By putting the ear against the ground, one may hear the tread of footsteps that are inaudible through the air alone.*

(5.) Production of Motion by Sound. If a tuning-fork be excited and its stem be pressed firmly against a table, the sound will become much louder. The solid fork communicates its vibration to the table, which in turn gives its vibration to a much larger body of air than that in contact with the fork alone. Tuning-forks are generally mounted upon resonance boxes, the whole body of air within, as well as the box itself, thus co-vibrating with the fork.

* Wheatstone invented a beautiful experiment to show the transmission of sound through wood. Upon the top of a music-box, he rested the end of a wooden rod reaching to the room above, and insulated from the ceiling by India rubber. A violin being placed on the top of the rod, the sounds from the box below filled the upper room, appearing to emanate from the violin.

(6.) Co-vibration Through Air as a Medium. The air between any source of sound and the ear is like an elastic spring between a pair of tuning-forks of the same size and material. When the prong of the first fork swings from a to b (Fig. 121), a condensation is propagated through the spring and makes

Fig. 121.



Tuning-forks Connected by a Delicate Wire.

the prong of the second fork swing slightly from x toward y. A rarefaction follows, making it swing from x toward z. The succession of these properly-timed impulses causes an accumulation of energy to be imparted through the air to the second fork, which soon gives forth an audible sound. The elastic bodies composing the ear in like manner accept vibrations from outside, and their motion is perceived as sound.

(7.) The Velocity of Sound depends on the ratio of the *elasticity* to the *density* of the medium through which it passes. The higher the elasticity,

the more promptly and rapidly the motion is transmittted, since the elastic force acts like a bent spring between the molecules; and the greater the density, the more molecules to be set in motion, and hence the slower the transmission.

Sound travels through air (at 32° F.) 1,090 feet per second. A rise in temperature diminishes the density of the air, and thus increases the velocity of sound. A difference of 1° F. makes a variation of a little more than one foot. Sound also moves faster in damp than in dry air.

Sound travels through water about 4,700 feet per second. Water being denser than air should on this account conduct sound more slowly; but its high elasticity (p. 10), measured by the amount of force required to compress it, more than quadruples the rate.

Sound travels through solids faster than through air. This may be illustrated by placing the ear close to the horizontal bar at one end of an iron fence, while a person strikes a sharp blow at the other end. Two sounds will reach the ear—one through the metal, and afterward another through the air. The velocity varies with the nature of the solid. In the metals it is from four to sixteen times that in air.

*Different sounds travel with sensibly the same velocity.** A band may be playing at a distance, yet

* It has been said that the "heaviest thunder travels no faster than the softest whisper." Mallet, however, found that in blasting with a charge of 2,000 lbs., the velocity was 967 feet per second, while with 12,000 lbs. it was increased to 1,210 feet. Parry in his Arctic travels states that, on a certain occasion, the sound of the sunset-gun reached his ears before the officer's word of command to fire, proving that the report of the cannon traveled sensibly faster than the sound of the voice.

the harmony of the different instruments is preserved. The soft and the loud, the high and the low notes reach the ear at the same time.

Velocity of sound used to find distance. Light travels instantaneously so far as all distances on the earth are concerned. Sound moves more slowly. We see a chopper strike with his ax, and a moment elapses before we hear the blow. If one second intervenes the distance is about 1,090 feet. By means of the second-hand of a watch or the beating of our pulse, we can count the seconds that elapse between a flash of lightning and the peal of thunder which follows. Multiplying the velocity of sound by the number of seconds, we obtain the distance of the thunder-bolt.

(8.) THE LOUDNESS OF SOUND depends chiefly on the amplitude of the vibration, if the air be quiet. The energy of the vibration is proportional to the square of the amplitude, *i. e.*, the arc through which the molecule swings to either side of its position of rest. But loudness is a sensation, and no accurate measurement of sensations has yet been made. The loudness of sound depends also on the density of the air. On the top of a mountain, because of the rare atmosphere, there are fewer molecules to be set in motion, hence the effect on the ear is less intense.

Mechanically considered, the intensity of sound diminishes as the square of the distance increases.* The sound-wave expands in the form of a sphere. The larger the sphere, the greater the number of air particles to be set in motion, and the feebler their vibration. The surfaces of spheres are proportional to the squares of their radii; the radii of sound-spheres are their distances from the center of disturbance. Hence the force with which the molecules will strike the ear decreases as the square of our distance from the sounding body increases.

Speaking-tubes conduct sound to distant rooms because they prevent the waves from expanding and losing their intensity.* The *ear-trumpet* collects waves of sound and reflects them into the ear. The *speaking-trumpet* is based on the same principle as the speaking-tube. The sound of the voice is strengthened also by the co-vibration of the walls of the trumpet.

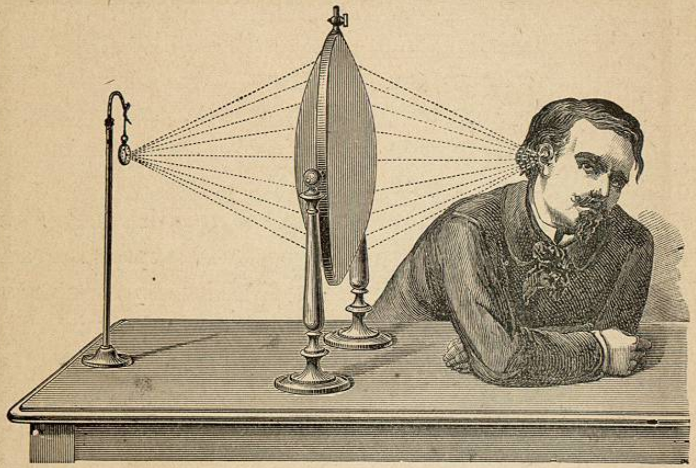
3. Refraction of Sound.—When a sound-wave goes obliquely from one medium to another, it is bent out of its course. Like light, it may be passed through a lens and brought to a focus. In Fig. 122 is shown a bag of thin India rubber or collodion, filled with carbonic acid gas so as to assume the form of a lens. A watch is placed at one focus of this and the ear at the other. The ticks of the watch can be heard, while outside the focus they are inaudible.

* The same proportion obtains in Gravitation, Sound, Light, and Heat. We have seen how the motion of the common Pendulum is due to the force of Gravity, and reveals the Laws of Falling Bodies. Now we find that the Pendulum, and even the principles of Reflected Motion and Momentum, are linked with the phenomena of Sound. As we progress further, we shall find how Nature is thus interwoven every-where with proofs of a common plan and a common Author.

* Biot held a conversation through a Paris water-pipe 3,120 feet long. He says that "it was so easy to be heard, that the only way not to be heard was not to speak at all."

4. Reflection of Sound.—When a sound-wave strikes against the surface of another medium, a portion goes on while the rest is reflected.

FIG. 122.



Refraction of Sound.

(1.) THE LAW is that of Motion;—the angle of incidence is equal to that of reflection.* If the reflecting surface be very near, the reflected sound will join the direct one and strengthen it. This accounts for the well-known fact that a speaker can be heard

* Domes and curved walls reflect sound as mirrors do light. Thus, in the gallery under the dome of St. Paul's Cathedral, London, persons standing close to the wall can whisper to each other and be heard at a great distance.—Two persons, placed with their backs to each other, at the foci of an oval room, or "Whispering Gallery," can carry on a conversation that will be inaudible to spectators standing between them.—The covered recesses on the opposite sides of a street, or the arches of a stone bridge, oftentimes reflect sound so as to enable persons seated at the foci to converse in whispers while loud noises are being made in the open space between these semi-domes.

more easily in a room than in the open air, and that a smooth wall back of the stand re-enforces the voice. The old-fashioned "sounding-boards" were by no

FIG. 123.

Reflection of Sound.

means inefficient, however singular may have been their appearance.

By revolving a disk of card-board from which a pair of sectors have been cut out, and blowing against it with a trumpet or whistle, a person stationed at the proper angle will notice a beating sound due to successive reflection and transmission of the waves.

(2.) ECHOES are produced where the reflecting surface is so distant that we can distinguish the reflected from the direct sound. If the sound be short and quick, this requires at least fifty or sixty feet; but if it be an articulate one, as in ordinary speech, more than a hundred feet are necessary. It is possible to pronounce and hear distinctly about five syllables in a second; 1,120 ft. (the velocity at a medium temperature) $\div 5 = 224$ ft.* If the wave travel 224 feet in going and returning, the advancing and returning sounds will not blend, and

* When several parallel surfaces are properly situated, the echo may be repeated backward and forward in a surprising manner. In Princeton, Ind., there is an echo between two buildings that will return the word "Knickerbocker" twenty times. So many persons visited the place that the city council forbade the use of the echo after 9 o'clock at night.—At Woodstock, England, an echo returns seventeen syllables by day and twenty by night. The reflecting surface is distant about 2,300 feet, and a sharp *ha!* will come back a ringing *ha, ha, ha!* —The echo is often softened, as in the Alpine regions, where it warbles a beautiful accompaniment to the shepherd's horn.—The celebrated echo of the Metelli at Rome is said to have been capable of distinctly repeating the first line of the Æneid eight times.—In Fairfax County, Va., is an echo which will return twenty notes played on a flute.—The tick of a watch may be heard from one end of the Church of St. Albans to the other.—At Carisbrook Castle, Isle of Wight, is a well 210 feet deep and twelve feet wide, lined with smooth masonry. When a pin is dropped into the well it is distinctly heard to strike the water.—In certain parts of the Colosseum at London the tearing of paper sounds like the patter of hail, while a single exclamation comes back a peal of laughter.—The dome of the Baptistery of the Cathedral at Pisa has a wonderful echo. During some experiments there, the author found every noise, even the rattle of benches on the pavement below, to be reflected back as if from an immense distance and to return mellowed and softened into music.—An interesting illustration of the reflection of sound is found at the so-called Echo River, of the Mammoth Cave, Ky. Sounding in succession the notes G, E, C, at the middle of the tunnel, the boatman receives the echoes, all mingled in to a full chord, for eight or ten seconds afterward.

the ear will be able to detect an interval between them. A person speaking in a loud voice squarely in front of a large smooth wall 112 feet distant, can distinguish the echo of the last syllable he utters; at 224 feet, the last two syllables, etc.

(3.) DECREASE OF SOUND BY REFLECTION.—If we strike the bell, represented in Fig. 120, before a vacuum is produced, we shall find a marked difference between its sound under the glass receiver and in the open air. Floors are deadened with tan-bark or mortar, since as the sound-wave passes from particle to particle of the unhomogeneous mass, it becomes weakened by partial reflection. The air at night is more homogeneous, and hence sounds are heard farther and more clearly than in the day-time.

(4.) ACOUSTIC CLOUDS are masses of moist air of varying density, which act upon sounds as common clouds do upon light, wasting it by repeated reflections. They may exist in the clearest weather. To their presence is to be attributed the variation often noticed in the distance at which well-known sounds, as the ringing of church bells, blowing of engine-whistles, etc.. are heard at different times.*

5. Musical Sounds.—(1.) THE DIFFERENCE BETWEEN NOISE AND MUSIC is that between irregular and

* The extinction of sound by such agencies is often almost incredible. Thus two observers looking across the valley of the Chickahominy at the battle of Gaines' Mill failed to hear a sound of the conflict, though they could clearly see the lines of soldiers, the batteries, and the flash of the guns.—These phenomena are ascribed by many to an elevation or a depression of the wave-front so that the sound passes above the observer or is stopped before it reaches him. See "Stewart's Physics," p. 141.

regular vibrations. Whatever the cause which sets the air in motion, if the vibrations are uniform and rapid enough, the sound is musical. If the ticks of a watch could be made with sufficient rapidity, they would lose their individuality and blend into a musical tone. If the puffs of a locomotive could reach fifty or sixty a second, its approach would be heralded by a tremendous organ-peal.*

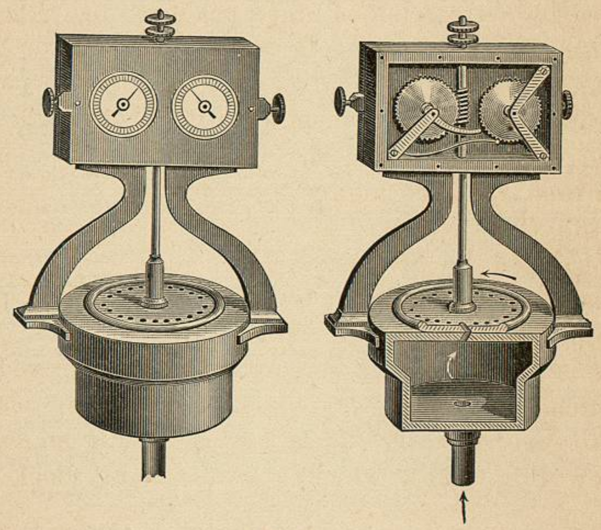
(2.) PITCH depends on the rapidity of the vibrations. Thus, if we hold a card against the cogs of a rapidly-revolving wheel, we shall obtain a clear tone; and the faster the wheel turns, the shriller the tone, *i. e.*, the higher the pitch.

(3.) THE NUMBER OF VIBRATIONS PER SECOND is determined by an instrument called the *siren*. It consists of a cylindrical box (Figs. 124 and 125), the top of which is pierced with a series of holes. Over this is a plate with a corresponding series, fixed to a vertical rod, which is pivoted on the lower plate so as to revolve easily. It is provided with an endless screw (Fig. 125), which operates some clock-work.

* The pavement of London is largely composed of granite blocks, four inches in width. A cab-wheel jolting over this at the rate of eight miles per hour produces a succession of 35 sounds per second. These link themselves into a soft, deep musical tone, that will bear comparison with notes derived from more sentimental sources, even though it may seem confused to a hearer in its midst. This tendency of Nature to music is something wonderful. "Even friction," says Tyndall, "is rhythmic." A bullet flying through the air sings softly as a bird. The limbs and leaves of trees murmur as they sway in the breeze. Falling water, singing birds, sighing winds, every-where attest that the same Divine love of the beautiful which causes the rivers to wind through the landscape, the trees to bend in a graceful curve—the line of beauty—and the rarest flowers to bud and blossom where no eye save His may see them, delights also in the anthem of praise which Nature sings for His ear alone.

On the dial (Fig. 124), we can see the number of turns made by the upper disk. The holes in the two disks are oppositely inclined, so that when a current of air is forced in from below it passes up through the openings in the lower disk, and striking against

FIG. 124. FIG. 125.



The Siren.

the sides of those in the upper disk, causes it to revolve. As that turns, it alternately opens and closes the orifices in the lower disk, and thus converts the steady stream of air into uniform puffs. At first they succeed each other so slowly that they may be counted. But, as the motion increases, they link themselves together, and pass into a full, melodious note. As the velocity augments, the pitch rises,