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AN ANALYSIS BY MOVIETONE OF A CRICKET'S CHIRP (*GRYLLUS ASSIMILIS*)

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Male crickets make a trilling, chirping sound by rubbing their front wings together. The under side of a strong transverse rib ("vein") near the basal end of each front wing bears a series of elevations forming the "file," figures 1 and 2. When the wings are rubbed from side to side this file scrapes on a slightly elevated spot on the upper side of the other front wing, setting the wings into up and down vibration. Since one wing, usually the right one,[1] is kept above the other, its file is the only functional one. A large, somewhat circular area near the distal end of each front wing suggests a drum-head and is supposed to increase the efficiency of the wing as a sound-producing organ.

If the wing be merely set into vibration, as when the head of a drum is struck, or a bow is drawn across a violin string, the pitch of the sound would depend on the natural periods of vibration of the wing as a whole and also of the complicated system of thin membranes and heavy veins which make up the wing (Fig. 1). However, the wing is attached at only a small basal part and is so soft that such vibrations of the wing as a whole would be quickly damped by air resistance. On the other hand, if each tooth of the file as it strikes the scraped surface makes the wings wave up and down once, causing an air-wave, a rapid succession of such waves would cause a sound independently of any natural period of vibration of the wing structures, although the two sounds might be combined to make up the chirp.

Kreidl and Regan (1905, Sitzungsberichte der Math.-Naturwiss. Klasse der K. Acad. der Wissenshaften, Wien, CXIV, pp. 57–81) carefully studied the chirp of a European cricket (*Gryllus campestris*). They found that the "file" had about 135 teeth, each about 0.14×0.04 mm. These rub on a raised surface about 1.5 mm. in diameter. By putting grease on the file and then noting where it was left after chirping they found that all of the teeth except a few small ones at the end were used. By putting a white dot on a wing and interrupting a beam of light so

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[1] Lutz, F. E., 1908, American Naturalist, XLII, p. 196.

Fig. 1. Under side of the dorsal part of the right front wing of a male cricket, the lateral part removed. The "file" is on the lower of two heavy cross-veins shown near the top of the figure.

that the dot appeared to stand still while the cricket was chirping, they concluded that there are six to eight complete (back and forth) strokes of each wing per second. This means that the wings go one way or another 12 to 16 times per second but, since while one is going right the other is going left, the approximately 131 teeth are rubbed at the rate of 131×24 to 32, making 3144 to 4192, teeth per second. The authors recorded the sound on a phonograph (presumably a wax cylinder) and counted the marks. From this record they calculated that the chirps are made by from 3157 to 4234 air vibrations per second, these figures agreeing well with the other calculation. They note that this pitch, which is near to the upper range of a piano, varies from one individual to another and also with the same individual, a statement which is doubtless true but the proof of which would depend upon the doubtful accuracy of the phonograph's speed.

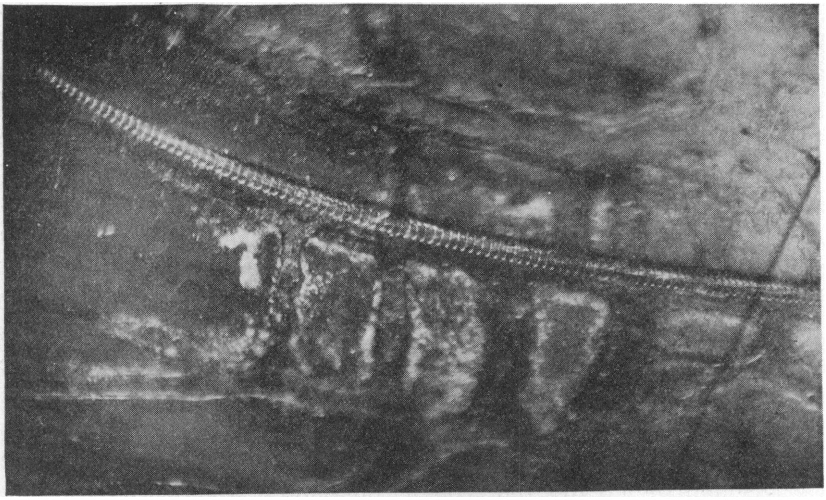

Fig. 2. Anterior (outer) portion of the "file," It may be oriented with respect to figure 1 by the four small cells shown below it in each figure.

In recent years a new method of recording and reproducing sound has been devised.[1] As utilized by the Fox Film Corporation for newsreel and studio production it is known as the Movietone System. It consists essentially of a microphone, which transforms sound-waves into electrical

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[1] The Western Electric Company apparatus.

energy, and amplifiers to increase the comparatively feeble microphone currents to values sufficient to cause a glow tube to flicker in exact correspondence with the frequency and intensity of the sound. This glow tube (called aeolight because of the alkali earth oxide used in one of its electrodes) is placed in the camera so as to affect a narrow track beside the picture strip of a "movie" film. This exposure is made through a quartz plate having a silver-plated coating in which there is a slit 0.0008″×0.12″. The emulsion side of the film passes over and close to the slit, back of which is the aeolight.

Since the lag of the aeolight is exceedingly small and since the speed at which the film passes the slit is very accurately controlled by an induction motor, this method of sound recording is excellent for frequencies within the normal audible range. For the recording of very shrill sounds at or beyond upper range of the human ear the film would have to be run faster than the usual ninety feet per minute and the aeolight burned more brightly to compensate for the decreased time of exposure. Other practical limitations, such as slit construction and adjustment, film emulsion characteristics, and so on, combine to fix a maximum of about 8000 cycles for practical sound recording by this method. Knowing the speed of the film, one has only to count the number of lines on this sound-track and do a simple calculation to determine the pitch of the sound. In this work the negative should be used to obviate the possibility of inaccuracy introduced by printing and processing. Film shrinkage is too slight to introduce a practical error. Since the greater the volume of the sound the greater the aeolight fluctuation, the density contrast in the photographic record becomes a measure of the volume of the sound, but it can be safely used only as an approximation to a relative measure and not exactly.

Since the apparatus will not practically record more than about 8000 cycles per second, it will not show possible harmonics generated in conjunction with fundamental sound vibrations in the neighborhood of 4000 cycles. Consequently, any harmonics which may be present in a cricket's chirp would be missed.

The cricket whose chirp was to be recorded was put into a small cage fitted with a front of high-quality optical glass to enable taking the picture part of the movietone. Illumination, when desired, was obtained from Cooper-Hewitt tubes and incandescent lamps fitted with reflectors. It was found that a sudden turning on of the lights did not cause the cricket to stop its chirping or even to change its position. Accordingly, to avoid as much as possible the heating effect of the lamps, they were kept on only when the recording apparatus was running.

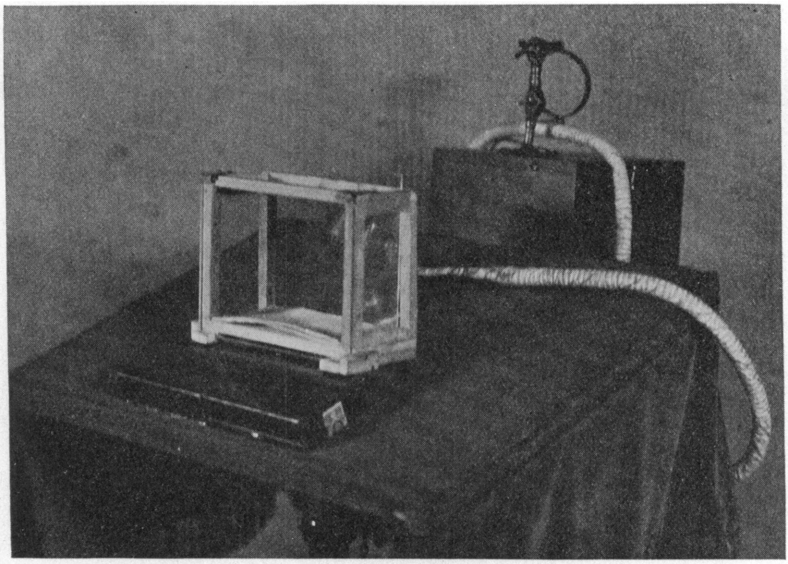

Fig. 3. Cage and microphone inside the sound-proof booth.

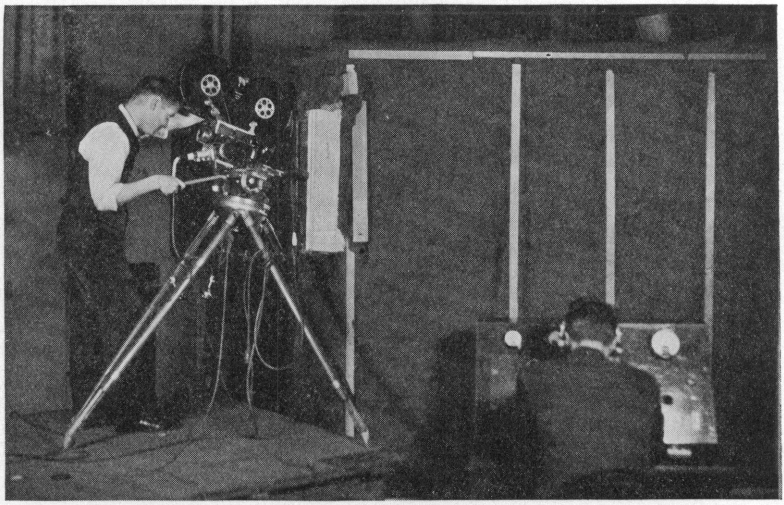

Fig. 4. The outside of the sound-proof booth and the movietone apparatus in use.

This cage was placed on a pedestal in a sound-proof booth. Close against the wire-screen back of the cage was put a highly sensitive Western Electric condenser microphone unit. Photographs of the apparatus are shown in figures 3 and 4. These photographs and, indeed, the opportunity to study the film are by courtesy of the Fox Company.

The chirping of *Gryllus*, as we hear it, seems to be a succession of shrill, slightly trilling notes lasting for about a tenth of a second and separated by pauses of about half a second, the number of notes per minute depending, within limits, on the temperature (unpublished observations, not to be confused with published records of *Œcanthus*, crickets belonging to a different subfamily). An interesting thing which an examination of this movietone showed at once is that each of what we hear as continuous sounds is made up of from two to four (rarely either one or more than four) separate "pulses" with intervals of quiet.

Apparently each of these pulses is due to a single scraping of the wings, the pauses between them representing the time required by the cricket for changing the direction of wing movement or else for getting back to the starting point. The fact that there is no record of sound between the pulses indicates that the wings do not continue to vibrate after the rubbing stops (see below concerning the number of vibrations as compared with the number of teeth) or that, if vibrations do continue, either the amplitude is not sufficient to affect the microphone or they are vibrating at a frequency above about 8000 cycles per second.

Out of about 70 chirps measured to describe this feature, 48 consisted of only three pulses each, and 15 had four pulses. Five had only two pulses and several were too faint or irregular to measure, they appearing to be trials at chirping rather than real chirps. The intervals between the pulses averaged 0.017 second (extremes, 0.011 and 0.025) and there were no significant differences between the average lengths of the successive intervals. Since the ordinary human ear does not clearly distinguish a pause of about 0.02 second, the succession of pulses seems to it to be a continuous or, at best, a slightly "wobbly" sound.[1] The

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[1] The inability of the human ear to catch very short pauses in sound has an important bearing on the discussion of the frequently reported synchronism of tree-cricket chirps. Lutz (1924, 'Insect Sounds,' Bull. Amer. Mus. Nat. Hist., L, p. 357) said: "Two *Œcanthus nivæus* were on one of my vines chirping in what seemed to be perfect unison. They were about six feet apart and I took a position about midway between them. Then, by careful concentration I could listen to one without paying attention to the other. One was averaging 105 chirps per minute and the other 107. Such being the case, there could not be unison, yet the chirps were so rapid and it was so difficult to keep my attention fixed on both at once that, even when I tried, I could scarcely detect the instant at which one of the insects was silent while the other was chirping. . . . Chirping in unison, a thing that would be ideal proof that tree-crickets hear each other if it were true, does not seem to be as definitely established as one could wish it were." In the absence of definite data for high-pitched, low-amplitude notes, let us suppose that the human ear, like the human eye, does not perceive pauses of less than about one-sixteenth of a second. It will be an interesting exercise in rather simple mathematics for those who are convinced of synchronism to calculate the relative number of times per hundred chirps that an average man could detect the "independent" chirps of the two crickets just mentioned. Since there are no published data concerning the relative lengths of sound and pause in the *Œcanthus* chirp, the present data for *Gryllus* might be used, making the ratio as 1 is to 5. However, if the rate of chirping of an individual cricket is dependent upon temperature, clearly there can be no synchronism unless all of the crickets are at the same temperature.

pauses between chirps (not the definite cessations from chirping) range from 0.28 to 2.88 seconds, this maximum time possibly being an actual stop, although full stops usually last much longer than three seconds. The average pause between chirps was 0.51 seconds.

In speaking of the pulses which make up a single chirp, it is desirable to number them backwards. This is because it was found that, while there was rarely any doubt about the last pulse, the chirps sometimes start off with faint, short bits of sound-record which may be separate pulses or merely an interrupted first pulse.

Considering the 63 chirps referred to above as having at least three definite pulses, the time consumed by the last pulse averaged 0.027± 0.0003 secs.; by the next to the last, 0.025±0.0003 secs.; by the second from the last 0.018±0.0004 secs.; and for the fifteen third from the last pulses the average duration was 0.006 seconds (extremes, 0.002 and 0.008).

In other words, the average tempo of the chirping of this specimen of *Gryllus assimilis* under the conditions of the experiment was:

Sound.—	(0.006)		0.018		0.025		0.027	
Interval.—		(0.017)		0.017		0.017		0.5

Each pulse usually starts and ends faintly, as is shown by the relative intensities of the lines on the sound-record (see Fig. 5), but there is no practical way of making this statement more concrete.

A further interesting thing about these pulses is their definite shift of pitch. Pitch can be determined from the sound record either by counting the number of cycles in a unit length of film (unit portion of a second) or by measuring the amount of film occupied (time taken) by a unit number of cycles. Both methods were used, each on a different part of the film.

Taking up the first method, the film was studied under a magnification such that one division of the micrometer scale had a time equivalent of 0.0001 second and the number of cycles (to the nearest complete cycle) was recorded for successive twenty-division units. Since the pulses regularly start and end weakly, it usually happened that there are a few cycles (rarely more than five or six) at each end of the pulse which had to be neglected because of uncertainty. This and the previously mentioned fact that the counting was done to only the nearest complete cycle, ignoring fractions of a cycle, should be remembered in what follows, but these sources of error seem unimportant for the use made of the data. There is a further qualification to what follows: Since we are to consider a shift in pitch during a pulse, only reasonably long pulses will be considered, namely those lasting at least eight time-units, about 0.016 second.

With these qualifications, we found the averages shown in Table 1.

Table 1.—Average Number of Cycles per Second in Successive Periods of 0.002 Second.

0.002 Second Units	Second from Last Pulse	Next to Last Pulse	Last Pulse
First	4619	4603	4636
Second	4690	4647	4664
Third	4667	4675	4692
Fourth	4738	4690	4720
Third from Last	4667	4531	4622
Second from Last	4595	4502	4510
Next to Last	4357	4473	4356
Last	4286	4300	4258
No. of Observations	20	33	34

To be oriented with respect to the familiar musical scale, one should remember that "middle C" of a piano as usually tuned has 256 cycles per second and that each higher octave has twice the number of the preceding one. Hence, the fourth C (called C'''') above "middle C" has 4096 cycles per second; D'''' has 4608; and E'''' has 5120. Accordingly, these figures indicate that the cricket was chirping, so far as its fundamental notes were concerned, in the octave just beyond piano range, and that each pulse starts at about D'''', rises a bit, maintains that note and then suddenly drops nearly a full note to almost within piano range. Such a performance would, in musical terms, be called a beautifully executed "slur" such as would be possible for an expert violinist, except that the cricket does it in less than 0.03 second and then in less than 0.02 second repeats it almost exactly. How exactly is indicated by the fact that among the 969 time-units for which the number of vibrations were counted to the nearest complete cycle (including those in the middles of the pulses) none had less than 8 cycles and none more than 10, representing a range of from 3810 to 4762 cycles per second. However, for the reasons mentioned above, the exact details of these statements should not be taken too seriously. Somewhat greater accuracy was obtained by the considerably more laborious method of measuring under a higher magnification the time taken for successive groups, each of five complete cycles.

The microscope was set so that each division of the micrometer was the equivalent of 0.0008 inch of film or 0.00004 second of time and the results shown in Table 2 were obtained.

Table 2.—Average Number of Cycles per Second in Successive Five-cycle Groups.

Groups	Next to Last Pulse	Last Pulse	Last Minus Next to Last
First	4427±16	4476±17	+49±23
Second	4434±12	4484±15	+50±19
Third	4482±14	4499±11	+17±18
Fourth	4474±12	4556±18	+82±22
Fifth	4499±15	4531±14	+32±21
Sixth	4523±13	4546±13	+23±18
Fifth from Last	4514±12	4499± 8	—15±14
Fourth from Last	4438±11	4468±16	+30±19
Third from Last	4365± 9	4357±10	— 7±13
Second from Last	4366±14	4308±11	—56±18
Next to Last	4263±10	4202±12	—61±16
Last	4197±14	4140±14	—34±20

These measurements, taken in a different way on a different part of the film, confirm the statement that a pulse starts at a fairly high pitch, increases somewhat, and then drops to a relatively low pitch. It will be noted, furthermore, that the average last pulse of a chirp starts at a somewhat higher and ends at a somewhat lower pitch than the average one which precedes it. The differences, taken singly group by group and considering their probable errors, are not highly significant but, taken as a whole, indicate that this may be true, especially as the less detailed data given in Table 1 are in accord. The possible meaning of this will be discussed later.

There are two points concerning which one could wish more definite information than the available data give. One is as to whether each sound cycle corresponds to a tooth of the file and the other is as to whether the wings scrape in each direction, it being possible but not generally believed that they scrape only in one position and then return to the starting point without scraping.

It has been mentioned that Kreidl and Regan, watching a white dot on a wing by interrupted light, estimated that the wings of *Gryllus campestris* swing back and forth six or eight times per second. We have shown (page 7) that in a single chirp of *Gryllus assimilis* the lengths of individual pulses not only vary but that the average lengths of the different pulses vary; also, that there is a variable but relatively considerable pause between chirps. If the same thing be true of *Gryllus campestris* it would seem that the strobloscopic method would give no or at least quite unreliable information concerning the rhythm of the wing-strokes. Since Kreidl and Regan lay great stress on their findings, it is to be presumed that *Gryllus campestris* has a more constant and continuous rhythm than our specimen of *Gryllus assimilis.*

If, for purposes of discussion and comparison, we consider that an average chirp of *Gryllus assimilis* under the conditions of the experiment is made up of three pulses each 0.023 second long with two intervals of 0.017 second and that there is a pause of 0.5 second between chirps, each chirp and pause would last about 0.6 second or, stating it the other way around, there would be 1.67 chirps per second. Since we assume three pulses per chirp, this would mean five pulses per second; but since we included the half-second pause between chirps, this is not the RATE of the pulses. If each pulse be considered to take 0.023 second and each interval 0.017 second, the total time taken would be 0.04 second, or the rate of the pulses would be 25 per second. If each pulse represents a complete back and forth swing of the wings, there being a scraping in one direction only, this would also be the rate of the wing motions. If, on the other hand, the wings scrape in each direction and each pulse represents a scraping, the rate of wing motion would be only 12.5 complete swings per second. Considering the probability of differing speeds of different species or even individuals and the fact that our cricket may have been chirping in a higher temperature than theirs, the difference between the rate of wing motion given by them (say 7 per second) and 12.5 per second is not unreasonably large and would indicate that the wings scrape in each direction.

Unfortunately, the movietone pictures do not help us here because there are only 24 per second, but another indication that the wings scrape in each direction is the shortness of the interval between pulses. If it takes 0.023 second to scrape in one direction, it is not probable that the cricket can stop the motion in that direction, separate the wings so that they will not scrape while going in the opposite direction, return them to the starting point, stop that motion, bring the wings together again, and start a new scraping, all in 0.017 second.

Quite aside from the complicated physics of the natural periods of the wings vibrating as wholes and in parts, the number of vibrations in a pulse is a further indication that each fundamental air-wave is caused by definite up and down movement due to the scraping of an individual tooth. If any pulse had undoubtedly more cycles of sound-waves than there were teeth in a file, this idea would have to be abandoned. Of 109 pulses studied with this in view and having at least 80 cycles, twenty-seven had from 80 to 89, seventeen from 90 to 99, thirteen from 100 to 109, ten from 110 to 119, twenty-two from 120 to 129, nineteen from 130 to 138, and only one had more, it recording 142 cycles, the end ones being very faint and hazy. Since there were 180 teeth in the file of the cricket which made these chirps the idea is, to say the least, not thrown out of court on this count. Furthermore, if there be a similar variability in *Gryllus campestris,* it would suggest that Kreidl and Regan were not fully justified in taking a single—and that nearly the maximum—number, 131, as the basis of their calculation.[1]

A still further and rather more convincing indication that each sound-wave corresponds to a tooth is found in the comparison of the spacing of the teeth with the differences noted on page 9 between the last pulse and the one which precedes it.

Measuring in micrometer divisions (when each division =0.00024 inch) the distance occupied by 10 teeth, starting from the end of the file which is near the anterior (outer, as the wing is usually held) border of the wing, the distances occupied by successive ten teeth of the used file of the individual whose chirps were recorded on this film were 36, 35, 36, 38, 38, 40, 41, 41, 39, 39, 36, 36, 33, 31, 29, 28, 23 and 18 divisions. Clearly there is a regular, progressive change in the sizes or spacing of the teeth from one end of the series to the other and the larger (at least, farther from middle of one to middle of the next) teeth are nearest the front (outer) end of the file where the wing starts to bend over the side of the cricket's body.

If we suppose that the pitch of the sound, the number of cycles per second, depends upon the number of teeth scraped per second, this pitch would be a function of both the speed of the wing motion and the spacing of the teeth. If either of these were constant the pitch would then depend on the other. If each varied, changes in the pitch would depend

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[1] Kreidl and Regan give the width of a single tooth on the file of *Gryllus campestris* as 0.04 mm. It is not clear that this means 25 teeth per mm. because they say nothing concerning the spaces between teeth, but, as this space is relatively small at any rate, we may consider that such is an approximate average. Since they give the total number of used teeth as about 131, this would make the length of the file at least 5.24 mm. or at least 0.21 inch. The file of the *Gryllus assimilis* which made the present movietone record had 180 teeth on a file-length of 0.15 inch. This makes an average of 1200 teeth per inch, or about 0.02 mm. per tooth. Accordingly, it would seem that the Kreidl and Regan *Gryllus campestris,* as compared with our *Gryllus assimilis,* had a file-length about 1.4 as great, each tooth about twice as large, and takes about 3.5 times as long to make a stroke.

most upon the one which varied most. If the rate of wing motion were practically constant and one pulse were caused by scraping from the outer to the inner end of the file (spreading the wings apart), the next by scraping from the inner to the outer end (closing the wings), the effect would be that one pulse would start out at a low pitch (the teeth being large and, so, not many per unit distance), getting even a bit lower, and then increasing gradually and considerably as the region where there are more teeth per unit distance is reached. On the return stroke the sound would start at its highest pitch, gradually and for a relatively considerable time get lower, hold at its lowest for a bit and then slightly increase. Neither of these happens, as is shown by Tables 1 and 2. Therefore, either the fundamental pitch does not depend upon the rate of scraping teeth or the rate of wing motion is not constant.

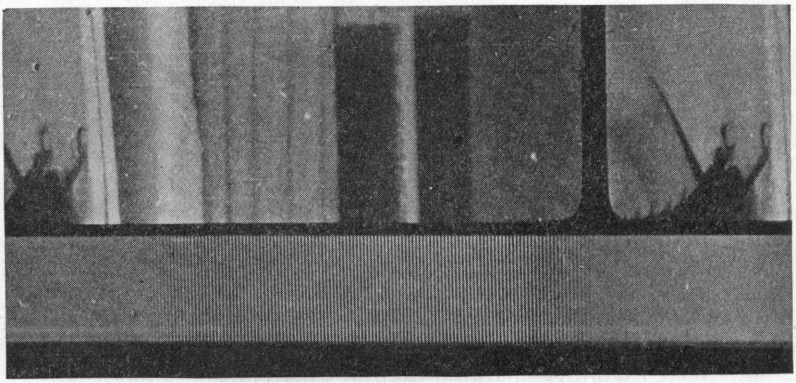

Fig. 5. Includes one "pulse" on the "sound-track." Note that the lines, each representing a sound-wave, are fainter at the ends than in the middle.

Suppose we take the latter alternative and, for the moment, disregard the variation in the size of the teeth. Then, Tables 1 and 2 would indicate that each wing stroke starts at a rather rapid rate (the pitch being fairly high), gets a little more rapid, holds that speed for a bit, and then slows up (the sound consequently decreasing in pitch) as the end of the stroke is reached in preparation for reversing the motion for the next stroke. This would give us the main feature of what we find and seems reasonable. Now add the variation in the teeth. As the wings spread apart the large (or wide-spaced) teeth are used first and, so, the pitch would be relatively lower than at the start of the closing of the wings when smaller (more per unit distance) teeth are used first. Likewise, the end of the spreading stroke would give a relatively higher pitch than the end of the closing stroke. It was remarked in connection with Table 2 (page 9) that the next to the last pulse of a chirp starts at a relatively lower pitch and ends at a relatively higher one than does the last pulse. This notion, then, appears to agree with the record and, furthermore, one might expect that a chirp would end with the wings closed although we know of no observations on this point.

A supplementary bit of evidence may be the fact that each pulse starts and stops faintly. (See page 7 and figure 5.) The teeth at each end of the file tend to be less distinct than those in the main part of the series and may, for this reason, make poor contact with the scraper. However, poor contact could, of course, be brought about by simply not pressing the wings close together. This is doubtless the explanation of faintness throughout many pulses, particularly the first one or two of a chirp.

On the whole, while freely admitting that not only are more data much to be desired but that some of the foregoing argument is on a rather slender thread, it seems fairly certain that crickets chirp by moving the wings in either direction, that each principal air-wave is caused by the "fanning" of the wing as a tooth goes over the scraper, and that the pitch of the sound is a direct function of the number of teeth scraped per second. If this be true, it might be expected that differing physiological and psycological states of the cricket would alter the pitch of its chirp.

Since the speed of such insect movements as have been studied has been found to be, within limits, a function of temperature, the chirping of a *Gryllus* would, presumably, be shriller at high than at low temperatures. This is very roughly confirmed by observations in the field but we have no accurate data. Those of us who have reared many crickets think that we can tell by intangible differences, possibly pitch, in their chirping "whether they are courting females, defying other males, or just passing the time" but here, again, we have no definite data. However, the present movietone record shows, out of the several hundred examined with this in mind, two successive chirps that were noticeably different from the rather monotonous remainder.

The first of these chirps started off with two pulses too weak to measure accurately and then ended with a strong pulse which reached a maximum of 9376 cycles per second and fell to a minimum of 8037, the average being 8195 cycles per second.[1] This was almost immediately followed by a second chirp of which the first pulse was too weak to measure, the second pulse ranged from 5626 to 5114 (average, 5544),

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[1] These rates are greater than the approximate "practical" maximum mentioned above for the recording apparatus. However, we believe that they are reasonably accurate. At least, there is no doubt about the chirp being abnormally shrill.

and the third (last) pulse ranged from 5626 to 4688 (average, 5200) cycles per second. What excited this cricket so that it chirped thus shrilly, reaching higher than D'''''' of our musical scale (more than five octaves above "middle D"), we do not know. Both before and after this it chirped "normally" but it showed that crickets can change the pitch of their chirping. Since there is no evident lower limit except the point where the waves are so slow that they will not blend into a continuous note, the cricket has a theoretical range of at least eight octaves but, since intensity of sound varies as the product of the squares of amplitude and pitch and since the amplitude of the cricket's chirp is at best small, at least we could not hear a low-pitched chirp.

If the fundamental pitch of a chirp is only a matter of fanning the air by the whole wing, of what use is the "drum-head" mentioned in our first paragraph and "supposed to increase the efficiency of the wing as a sound-producing organ"? Would a wing having the simple, network venation of the female cricket's wing but supplied with a file and scraper be just as efficient? Possibly. One thing that this drum-head probably does is to add to the sound-waves which we hear when a cricket chirps other notes of exceedingly high pitch and low amplitude which affect neither our ears nor the movietone film. It is made up of two small membranes supported by continuous rigid rims and, so, almost certainly these membranes have natural periodicities of vibration. If they are set vibrating by the rapid shaking of the whole wing it is quite possible that they may continue to vibrate in their natural periods even after the wing as a whole has stopped. If that be their only function it would imply either that the crickets can hear sounds far shriller and of much less amplitude than those recorded in the present experiments or that, the crickets not hearing them, even this function of the drum-head has no biological value.

It would be exceedingly interesting to determine whether there are, in fact, these supplementary components in the cricket's chirp, also what, if any, harmonics of the fundamental pitch there are. Furthermore, it would be of interest to get for comparison with the present record accurate data concerning the sounds made in a similar fashion by such insects as the katydid and also concerning sounds made in quite different ways by such insects as short-horned grasshoppers, cicadas, certain beetles, mosquitoes, and so on. There have arisen among insects very diverse methods of making sounds. Are all equally efficient and do they serve a really important purpose in the lives of the insects? If not, why have they developed and how?