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A Method of Calculating Hearing Loss for Speech from an Audiogram

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In the present paper a formula is developed for calculating the hearing loss for speech from an audiogram showing the hearing loss for each of a series of pure tones. The formula is based upon studies of loudness, including the determination of the relative contributions of different frequency regions to the audibility of speech at or near the threshold level. The formula is tested for each of 165 ears involving a wide variety of hearing losses. In every instance an audiogram is available and also an independent observation of the hearing loss for speech. The formula yields a calculated value which generally is in closer agreement with the observation than is the value calculated by the familiar rule of averaging the losses at 500, 1000, and 2000 c.p.s. The agreement is particularly better when the audiogram is not "flat." A simplified computational rule, indicated by the more complete formula, is found within indicated limits to be almost as reliable as the formula. This simplified rule is to examine the hearing losses measured by means of the audiometer at the three frequencies 500, 1000, and 2000 c.p.s., and to take the average of the two smallest values of loss.

THE usual practice at the present time for testing the degree of deafness of a person is to use a tone range audiometer and make an audiogram. This audiogram shows the hearing loss for pure tones usually taken at octave intervals. It is believed by many that an additional test for the hearing loss for speech is necessary. Some, however, are content to take an average value of the hearing loss at 500, 1000, and 2000 c.p.s. as the hearing loss for speech. Indeed, this does give an approximately correct value when the audiogram is not changing rapidly with frequency.

A more accurate formula is developed here which is applicable to all types of audiograms and gives the correct result within the observational error of making such tests.

In a paper by W. A. Munson and the author[1] it was found that the loudness N in sones is given by

$$N=\int_0^{100} N_x dx, \tag{1}$$

where N_x is the loudness per patch of nerves and x is the position coordinate of the nerve endings in the ear. The quantity x is the percent of nerve endings passed over in going from the helicotrema to the position x.

Loudness measurements upon different sounds indicate that near the threshold the quantity N_x is equal to the stimulation intensity or

$$N_x=(I/I_0), \tag{2}$$

where I is the intensity of sound in a critical frequency band width $(\Delta f)_c$ of speech measured in the air near the listener's ear, and I_0 is the corresponding intensity for this band of speech to be at the threshold level of hearing—that is, zero stimulation level.

These intensities may be expressed thus:

$$I=10^{-16}(\Delta f)_c\times 10^{B/10} \tag{3}$$

$$I_0=10^{-16}\times 10^{(\beta_r+\beta_H)/10}, \tag{4}$$

where B is the spectrum level of speech including peaks; $(\Delta f)_c$ is the critical band width in c.p.s.; β_r is the threshold intensity level for hearing critical bands of

[1] H. Fletcher and W. A. Munson, "Relation between loudness and masking," J. Acous. Soc. Am. 9, 1 (1937).

TABLE I.

(1) Observer	(2) Obs. β_s	(3) Calc. β_s	(4) 3-average β_s	(5) 2-average β_s	(6) Hearing loss $f=250$	(7) 500	(8) 1000	(9) 2000	(10) 4000
B–3R	31	38	40	38	32	42	37	41	41
B–4L	44	35	40	36	42	47	41	31	80
B–5L	51	49	52	51	58	55	56	46	48
B–5R	52	53	52	51	50	50	55	52	65
B–6L	52	53	55	52	50	54	50	60	60
B–6R	51	53	55	51	50	50	55	52	65
B–7R	53	45	47	45	51	50	47	43	50
B–9L	64	65	67	65	50	60	71	71	70
B–9R	68	67	72	68	52	60	80	76	79
B–7L	65	72	73	72	71	75	74	70	80
B–3L	90	86	89	87	95	95	83	90	90
RR–R	61	61	63	61	70	65	66	58	55
RR–L	55	53	56	53	62	60	57	52	44
RA–R	66	74	79	72	72	75	92	70	80
RC–L	56	55	55	53	47	52	58	54	80
BD–R	73	77	86	78	77	83	90	74	80
DL–L	58	62	66	66	66	64	68	67	50
HM–R	49	58	63	62	60	62	65	62	50
HB–R	57	65	68	66	63	72	70	62	100
HB–L	56	63	67	64	52	58	73	70	78
FB–L	59	67	68	66	56	62	72	70	82
FS–R	28	32	35	32	27	25	39	41	45
BL–L	89	87	97	94	70	90	98	102	106
WW–L	70	70	73	69	55	66	72	82	102
1R	−2	−2	2	−2	15	10	−5	0	25
1L	−3	−2	3	−2	20	15	0	−5	25
2R	−9	−5	−8	−10	10	−5	−10	−10	−10
2L	−5	−8	−5	−7	5	0	−10	−5	−5
3R	22	20	25	20	35	35	20	20	10
3L	30	21	40	37	45	45	35	40	15
4R	18	18	30	27	40	35	35	20	10
4L	18	17	32	30	45	40	35	25	0
5R	−8	−7	−5	−8	10	0	−5	−10	−5
5L	−1	0	5	−2	15	10	−5	10	−5
6R	25	22	28	25	30	30	35	20	10
6L	20	19	25	22	30	30	30	15	10
7R	26	25	37	32	35	45	40	25	15
7L	13	12	17	15	35	20	20	10	0
8L	47	45	47	45	60	50	45	45	35
9R	18	12	18	15	40	25	20	10	0
9L	18	10	17	13	40	25	15	10	−5
10R	8	−6	0	−5	15	10	0	−10	−10
10L	−8	−8	−7	−10	5	0	−10	−10	−5
11L	30	33	38	35	55	45	40	30	30
12R	18	31	38	35	45	45	35	35	15
12L	30	31	40	37	60	45	40	35	15
13L	58	65	70	65	80	80	65	65	55
14R	18	28	32	27	40	40	30	25	45
15L	32	19	27	22	35	35	30	15	35
16R	73	72	73	70	65	70	70	80	35
16L	36	32	43	40	55	50	50	30	20
17R	47	44	53	47	65	55	40	65	85
17L	58	55	63	57	70	65	50	75	90
18R	18	20	20	20	20	20	20	20	25
18L	15	9	12	10	25	15	5	15	15
19R	13	12	13	13	15	15	10	15	20
19L	8	7	8	8	15	10	5	10	25
20L	68	62	67	63	65	75	65	60	50
21R	57	64	68	67	50	70	70	65	60
21L	53	67	68	65	50	60	75	70	80
22R	37	38	43	40	35	30	50	50	55
23R	8	4	8	3	10	5	0	20	30
23L	3	3	7	0	10	5	0	15	40
24R	13	13	17	10	15	10	10	30	40
24L	23	34	33	32	20	30	35	35	45
25R	30	32	39	32	40	35	30	50	80
25L	70	72	73	70	65	65	75	80	45
26R	58	60	60	60	65	60	60	60	85
26L	8	13	10	8	20	10	5	15	65
27R	10	12	13	12	20	15	10	15	35
28R	55	61	65	60	50	60	60	75	75
29R	5	4	23	3	15	5	0	65	60

TABLE I.—(*continued*).

(1) Observer	(2) Obs. β_s	(3) Calc. β_s	(4) 3-average β_s	(5) 2-average β_s	(6) Hearing loss $f=250$	(7) 500	(8) 1000	(9) 2000	(10) 4000
29L	−5	−8	−5	−10	5	−10	−10	5	5
31R	75	79	83	82	65	85	85	80	85
31L	80	77	80	78	80	85	80	75	65
32R	62	62	65	62	70	70	60	65	60
32L	77	69	78	73	80	90	80	65	80
33R	53	50	48	48	45	45	50	50	55
33L	57	63	62	60	60	60	60	65	60
34R	58	58	60	58	55	60	65	55	55
34L	7	2	3	3	0	5	5	0	20
35R	10	17	17	15	20	15	15	20	40
35L	63	57	57	55	45	50	60	60	60
36R	52	52	55	53	55	60	50	55	70
36L	45	43	47	43	60	55	45	40	55
38R	10	3	5	3	25	10	5	0	5
38L	58	59	58	58	70	55	60	60	60
39R	63	58	62	58	55	70	60	55	55
39L	33	35	35	35	30	35	35	35	60
40L	40	41	43	42	45	45	40	45	35
41R	33	40	40	40	35	40	40	40	55
41L	40	42	45	42	35	35	50	50	55
42L	38	42	47	42	50	55	40	45	40
43L	27	25	27	25	40	30	20	30	30
44L	10	−3	−2	−2	5	0	−5	0	45
45R	57	47	60	60	30	60	60	60	60
45L	13	12	15	13	25	20	10	15	20
46L	3	3	5	3	20	10	5	0	10
47R	5	5	5	5	10	5	5	5	15
47L	30	30	30	30	30	30	30	30	25
48R	12	8	10	10	25	10	5	15	45
48L	7	2	8	3	10	20	0	5	40
49R	15	13	15	13	15	20	15	10	15
49L	52	47	50	50	45	50	55	45	35
50R	15	9	20	10	25	30	15	5	35
50L	25	24	32	25	40	45	30	20	55
51R	43	51	52	50	45	50	50	55	55
51L	40	43	47	43	40	45	55	40	50
52R	22	19	22	20	20	25	25	15	15
52L	−8	−9	−8	−10	0	−5	−10	−10	−5
53R	9	8	13	8	20	25	10	5	20
53L	11	11	12	10	15	15	10	10	30
54R	−7	−8	−7	−7	10	−5	−10	−5	−5
54L	−7	−7	−3	−5	5	0	−10	0	−5
55R	12	13	17	15	20	20	20	10	15
55L	−3	−4	−2	−5	10	5	−5	−5	10
56R	10	−6	0	−2	0	5	−10	5	−10
56L	12	10	10	10	5	10	10	10	10
57R	15	12	8	10	10	10	10	15	25
57L	13	12	12	10	15	10	10	15	25
58R	10	4	10	5	25	20	10	0	10
58L	5	5	7	5	10	10	5	5	0
59R	0	5	5	5	5	5	5	5	10
59L	5	0	5	5	0	5	5	5	5
60R	1	4	3	3	10	0	5	5	5
60L	8	3	7	3	20	15	0	5	5
61R	8	3	5	3	15	5	0	10	15
61L	7	1	2	0	15	5	0	0	−5
62R	4	4	3	3	5	0	5	5	0
62L	7	7	8	5	0	5	5	15	0
63R	16	26	33	30	10	30	40	30	60
63L	38	31	35	33	15	30	40	35	65

speech located at various frequency positions for a person of average hearing—that is, zero hearing loss at all frequencies as measured on a standard audiometer; and β_H is the hearing loss measured on a standard audiometer.

Therefore,

$$N_x = (\Delta f)_c 10^{(B-\beta_T-\beta_H)/10}. \quad (5)$$

The relation between x and f is obviously given by

$$dx=((\Delta x)_c/(\Delta f)_c)df, \quad (6)$$

where $(\Delta x)_c$ is the critical change in x corresponding to $(\Delta f)_c$.

If these values of N_x and dx from Eqs. (5) and (6) are substituted in Eq. (1) there results

$$N_H=\int_0^\infty (\Delta x)_c 10^{(B-\beta_r)/10}\cdot 10^{-\beta_H/10}df. \quad (7)$$

The value N_H is the loudness for an individual with a variable hearing loss β_H with frequency. The value of the critical change $(\Delta x)_c$ of the position coordinate is considered constant at all positions and has been found to be 1.56 percent, corresponding to about one-half millimeter on the basilar membrane.

Consider a person who has a uniform hearing loss β_s at all frequencies—that is, a flat audiogram. Such a person will obviously also have a hearing loss β_s for speech. The loudness N_s of speech near the threshold for such a person is, then,

$$N_s=(\Delta x)_c 10^{-\beta_s/10}\int_0^\infty 10^{(B-\beta_r)/10}df. \quad (8)$$

Now, at the threshold level the values of N_H and N_s are equal for these two cases, and so

$$10^{-\beta_s/10}=\frac{\int_0^\infty 10^{(B-\beta_r)/10}\cdot 10^{-\beta_H/10}df}{\int_0^\infty 10^{(B-\beta_r)/10}df}=\int_0^\infty G.10^{-\beta_H/10}df, \quad (9)$$

where

$$G=\frac{10^{(B-\beta_r)/10}}{\int_0^\infty 10^{(B-\beta_r)/10}df}. \quad (10)$$

It is seen from Eq. (9) that to find the hearing loss for speech a weighted average of the exponential $10^{-\beta_H/10}$ must be taken. The factor G can be obtained from

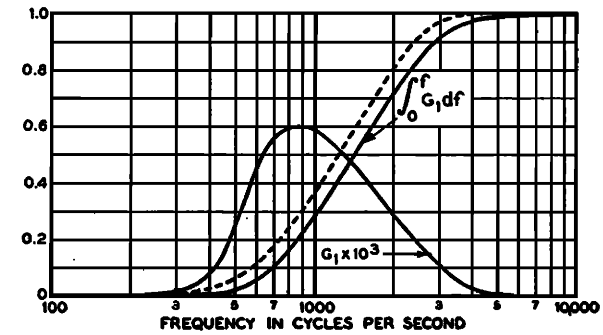

Fig. 1.

Table II.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
			3-average	2-average	Hearing loss				
Observer	Obs. β_s	Calc. β_s	β_s	β_s	$f=250$	500	1000	2000	4000
RW–R	41	47	53	45	45	40	50	70	78
RW–L	41	38	51	41	45	30	54	70	62
WW–R	60	69	78	72	54	66	78	90	110
WW–L	70	70	73	69	55	66	72	82	102
PP–L	65	64	74	70	48	63	77	83	75
PP–R	63	57	70	65	38	59	72	80	70
IS–R	52	45	47	40	36	36	43	63	85
MC–L	40	36	52	41	21	33	50	73	86
TH–R	57	44	62	50	27	45	55	85	80
TH–L	58	45	59	48	30	40	55	82	80
B–8L	57	50	61	57	32	47	70	67	69
B–8R	58	57	62	58	40	48	68	69	67
B–10R	60	69	65	57	50	52	61	82	77
B–10L	73	70	75	69	55	61	77	88	80
8R	45	37	48	42	55	60	45	40	20
11R	33	34	42	37	55	50	45	30	30
13R	53	58	65	60	75	75	65	55	55
14L	28	33	47	35	55	50	40	30	60
15R	43	34	47	43	55	55	55	30	35
20R	43	39	45	43	40	30	55	50	45
22R	37	38	43	33	35	30	50	50	55
22L	32	28	40	28	20	20	45	55	65
27L	20	22	30	20	15	20	20	50	60
28L	13	14	27	15	30	20	10	50	50
30R	25	27	42	30	20	20	40	65	65
30L	24	22	23	30	10	15	45	80	75
37R	53	53	63	57	80	75	65	50	50
37L	38	39	45	40	65	55	45	35	45
40R	55	49	58	53	65	70	60	45	45
42R	46	49	57	52	60	65	60	45	50
43R	57	53	58	53	75	70	55	50	60
44R	33	37	45	40	40	55	45	35	30
46R	40	34	42	38	55	50	45	30	30

measurements of B and β_r. It will be noticed that only relative values of either B or β_r are necessary since adding a constant quantity to either will not change the value of G.

An approximation to Eq. (9) is

$$10^{-\beta_s}=W_1 10^{-\beta_1/10}+W_2 10^{-\beta_2/10}+W_3 10^{-\beta_3/10}+W_4 10^{-\beta_4/10}+W_5 10^{-\beta_5/10}, \quad (11)$$

where β_1 is hearing loss at 250 c.p.s., β_2 is hearing loss at 500 c.p.s., β_3 is hearing loss at 1000 c.p.s., β_4 is hearing loss at 2000 c.p.s., and β_5 is hearing loss at 4000 c.p.s., where the weights are given by

$$W_1=\int_{175}^{350}Gdf,\quad W_2=\int_{350}^{700}Gdf,\quad W_3=\int_{700}^{1400}Gdf,$$
$$W_4=\int_{1400}^{2800}Gdf,\quad W_5=\int_{2800}^{5600}Gdf. \quad (12)$$

The values of the average speech spectrum level B_s are known from Dunn and White's data.[2] But speech is a varying rather than a steady sound. The threshold is determined by intensity levels higher than the average by an amount ΔB_s which may vary with the fre-

[2] H. K. Dunn and S. D. White, "Statistical measurements on conversational speech," J. Acous. Soc. Am. 11, 278 (1940).

quency range. The relative values are not known. They may be related to the peak levels given by Dunn and White.

The values of β_r are related to the field threshold levels for pure tones as given by the zero loudness contour. Evidence discussed in the paper referred to above indicates that at the low frequencies the threshold for a critical band of speech is somewhat higher by an amount $\Delta\beta_r$ than the threshold level β_r for a pure tone at the center of the band.

So the value

$$B-\beta_r=B_s-\beta_r+\Delta B_s-\Delta\beta_r.$$

The values of B_s and β_r are known with considerable accuracy but even the relative values of $\Delta B_s-\Delta\beta_r$ are not known.

From measurement of speech threshold levels for various filter systems and for listeners of normal hearing values of G were obtained as shown in Fig. 1. Using these values the weights W_1 to W_5 were calculated to be approximately 0.003, 0.097, 0.4, 0.4, and 0.1. The data for determining the values of G are rather scattered and are not inconsistent with weights 0.02, 0.16, 0.4, 0.4, and 0.02, which were found to give a better fit for the 165 cases of deafened ears considered in this paper. The dotted curve in Fig. 1 corresponds to these weights so a comparison between observed results and those calculated by Eq. (11) using these weights will be shown.

Three sets of data with audiograms and corresponding hearing losses for speech are available. The first set is given in my book.[3] The second set is in the book entitled *Hearing Aids*.[4] The third set was taken by Curry and Powers of the Bell Telephone Laboratories and has not heretofore been published.

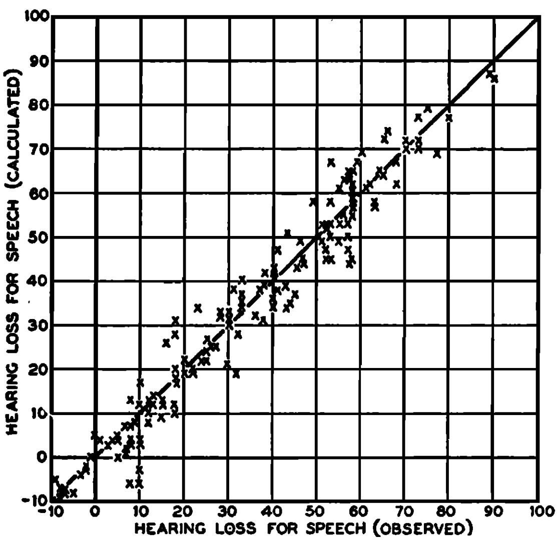

FIG. 2.

In the first set two different ways of determining the hearing loss for speech were used. In the first one the speech sounds were called directly through the air and the distance to the ear was varied. In the second one, the sounds were reproduced by a phonograph. An average of these was taken as observed β_s.

In the second set of data taken at Harvard University three ways of determining β_s were used, namely (1) spondee word lists; (2) phonetically balanced word lists; and (3) sentences. An average of these three methods was taken as observed β_s.

The third set used a phonograph record on which the spondee list of words was recorded by a man's voice. The technique used for determining the threshold level for speech was the same as for pure tones. The persons tested were those entering the New York Eye and Ear Infirmary during the period these tests were made. The readings were taken on the attenuator used on the audiometer which gives losses in 5-db steps but the zero for speech loss was arbitrary. There were 126 ears tested. The setting on the attenuator dial corresponding to zero speech loss was chosen to give the best agreement for those having hearing near normal.

These three sets of data were divided into two groups. In group (1) shown in Table I only those are included in which the hearing loss for the 500 cycle tone differed from that for the 2000 cycle tone by less than 20 db. In group (2) shown in Table II the remainder of the data is given. In column 1 is listed the designation for the deafened observer. In column 2 the values for observed hearing loss β_s for speech are given. In column 3 the values calculated by Eq. (11) using weights 0.02, 0.16, 0.4, 0.4, and 0.02 are given. In column 4 the values for the average hearing loss for 500, 1000, and 2000 cycles are given. In column 5 is given the average of the two smallest values out of three values for 500, 1000, and 2000 c.p.s. In columns 6, 7, 8, 9, and 10 are given the values of the hearing loss for the frequencies 250, 500, 1000, 2000, and 4000 c.p.s. In other words, these columns define the audiogram.

The R.M.S. difference between the observed β_s and the calculated β_s is 5.0 db, which is considered within the observational error. In other words, the agreement between the observed and calculated values is within the experimental error. A plot of observed *versus* calculated values of articulation for the third set of data is shown in Fig. 2.

The R.M.S. difference between observed β_s and 3-average (average for the three frequencies 500, 1000, and 2000) for the group in Table I is 6.5 db. This average for these uniform audiograms is almost as good as the calculated value, but it tends to be too low a hearing loss. However, in the group shown in Table II where the audiograms are not flat the corresponding R.M.S. values are 5.7 db and 9.0 db. The average for the three frequencies is always too high.

[3] Harvey Fletcher, *Speech and Hearing* (D. Van Nostrand Company, Inc., New York, 1929), pp. 217, 219.

[4] H. Davis *et al.*, *Hearing Aids* (Harvard University Press, Cambridge, Massachusetts, 1947).

The algebraic average is about 8 db higher than the observed values. An examination of Eq. (11) shows why this must be so. This suggested that the simple procedure of using the average of only the two lowest values of the three might yield results comparable in accuracy to the results obtained by the more involved calculation indicated in Eq. (11). For example, for hearing losses 30, 45, and 60 for 500, 1000, and 2000 c.p.s. the speech loss β_s according to this method is given by

$$\beta_s = (30+45)/2 = 37\tfrac{1}{2}.$$

Values calculated in this way are shown in column 5 under the heading 2-average. The R.M.S. difference between observed β_s and 2-average is only 5.1 db for this second group instead of 9.0. It is thus found that at least for these 165 cases this method can be used with confidence that in general it will yield values as accurate as the data in the usual audiogram. For extreme accuracy Eq. (9) using the dashed curve in Fig. 1 for values of G should be used. Either of the last two methods will yield greater accuracy than almost any of the speech tests which are usually made.

In conclusion it should be pointed out that the observed values for the hearing loss for speech given above are determined essentially from threshold values. This is true in spite of the fact that the criterion for determining whether the various speech sounds were heard is when the amplification was such that 50 percent of the words were interpreted correctly. If a more involved method which used all the speech sounds including the sentences were used, no doubt the hearing losses for speech for cases of nerve deafness would be somewhat greater than those given above.

APPENDIX

In a paper entitled "The perception of speech sounds by deafened persons" which will soon be published, a method of calculating articulation *versus* gain curves for any type and amount of deafness is given. In Fig. 3 are shown three such calculated curves. The first is for a person having zero hearing loss at all frequencies. The second is for a person having a 40-db conductive loss at all frequencies. The third is for a person having a flat audiogram of 40-db conductive loss and then an additional large nerve loss of 50 db above 2500 c.p.s.

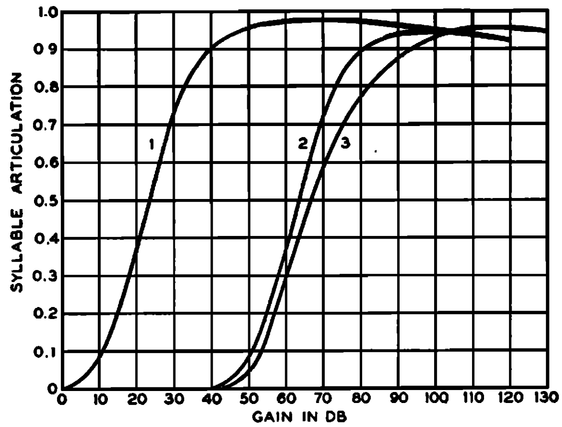

FIG. 3.

According to the 2-average method outlined in the paper, the hearing loss for the third case would calculate to be 40 db. However, the shift in the articulation *versus* gain curve at the 50 percent articulation level is 44 db or 4 db greater than 40 db. The articulation is given as percent of meaningless syllables of the type consonant-vowel-consonant that are interpreted correctly, the zero gain being taken as the value of gain to reach the threshold of hearing level for a person of zero hearing loss. In general, the hearing loss for such cases is somewhat higher than the 2-average value. An estimate of this excess can be made as follows. For the third case discussed this excess is seen to be 4 db. If f_c is the cut-off frequency for the audiogram or where the hearing suddenly becomes very large, this excess is given approximately by

$$4\times(2500/f_c)^2.$$

Or the total hearing loss for speech is given by

$$(\text{2-average})+4(2500/f_c)^2.$$