them with a prehistoric, mechanical punched card computer that produced an output of thousands of numbers. These numbers outlined not a picture of the structure I was trying to solve, but a mathematical abstraction of it: the directions and lengths of all the 25 million lines between the 5000 atoms in the hemoglobin molecule radiating from a common origin. I scanned the maps eagerly for interpretable features and was elated when they seemed to tell me that the molecule consists simply of bundles of parallel chains of atoms spaced apart at equal intervals.

'Shortly after my results appeared in print, a new graduate student joined me. As his first job, he performed a calculation which proved that no more than a small fraction of the hemoglobin molecule was made up of the bundles of parallel chains that I had persuaded myself to see, and that my results, the fruits of years of tedious labour, provided no other clue to its structure. It was a heartbreaking instance of patience wasted, an ever-present risk in scientific research. That graduate student was Francis Crick, later famous for his part in the solution of the structure of DNA.'

However, I must mention that in a very fine and perceptive lecture at the Annual Meeting of the Indian Academy of Sciences (1998), in Kottayam, T. V. Ramakrishnan pointed out that something worthwhile will come from our laboratories only if adequate funds (the 3rd G of the formula given by Paul Ehrlich, i.e. Geld – money) are provided to competent groups in the country. In this connection, I am tempted to tell the story which Lawrence Bragg related to me when he visited Madras. When Max Perutz had taken the X-ray photographs of haemoglobin crystals, Lawrence Bragg went to the Chairman of the Medical Research Council and asked him whether the Council would fund the Cavendish Lab to an extent of 1 million pounds over a period of 5 or 10 years to undertake the crystal structures of molecules of biological interest. In reply to the question asked by the Chairman of MRC, 'What will we get for it?', Lawrence Bragg replied 'one or two Nobel Prizes'. In fact, this investment resulted in 5 Nobel Prizes.

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SCIENTIFIC CORRESPONDENCE

An analysis of the stability of Wien bridge oscillator and a novel way of studying nonlinear devices

A Wien bridge oscillator[1–4] is a resistance–capacitance (*RC*) oscillator which is widely used for the generation of audiofrequency sine waves over a wide range of frequencies. In this paper, we have tried to find a relationship which relates the output voltage of the oscillator to the different resistances and the parameters of the nonlinear device used for stabilization of the output. This analysis shows a way to study nonlinear devices like semiconductor diodes using AC which is complementary to the standard method of studying these devices using DC. The analysis also shows that if we use a nonlinear device like a tunnel diode which has a more complicated forward characteristic for the stabilization of the oscillator, the device may be driven to a very interesting bistable situation.

An oscillator is a device by which we convert DC input to AC of a suitable frequency. A Wien bridge oscillator shown in Figure 1 is an oscillator whose frequency is given by $1/2\pi\,(RR'CC')^{1/2}$. Let the peak output voltage of the operational amplifier (op-amp 741C) be V. This voltage is fed back to the input of the amplifier via the *RC* combination. Components of several frequencies are present in the output when the DC power is switched on, but only the component resonant with the frequency given by the *RC* combination is fed back in the same phase as the output and consequently it is the only component that survives after the transients have died out. The feed back voltage is $V/3$. Two identical diodes in opposition (D_1 and D_2) are used to stabilize the output of the oscillator. The two diodes are active in the two halves of the sinusoidal output. We assume the reverse current through the diodes to be negligible. If the diodes and the R_1, R_3 combination produce an effective resistance $2R_2$, then the gain of the non-inverting op-amp is 3. So the loop gain is unity and all the so-called Barkhausen conditions are satisfied, making sustained oscillation possible. We are interested in finding the output voltage of the oscillator in terms of the different resistors in the circuit and the diode voltage drop.

If the steady state peak output voltage is V, then $2V/3$ must be the drop across R_1, and the same voltage drops across the diodes and R_3 combination. The rest, $V/3$, drops across R_2. If the current through R_2 is I and through R_1 is I_1 we have

$$I=\frac{V}{3R_2}, \qquad (1)$$

and

$$\frac{2V}{3}=V_d+I_d R_3=I_1R_1, \qquad (2)$$

where I_d and V_d are the peak current and peak voltage drop across the diode when the peak output voltage is V. We have worked at low frequencies of the order of a few hundred Hertz. In this region, the output voltage does not depend on the frequency and there is no phase lag between the output and the diode voltage

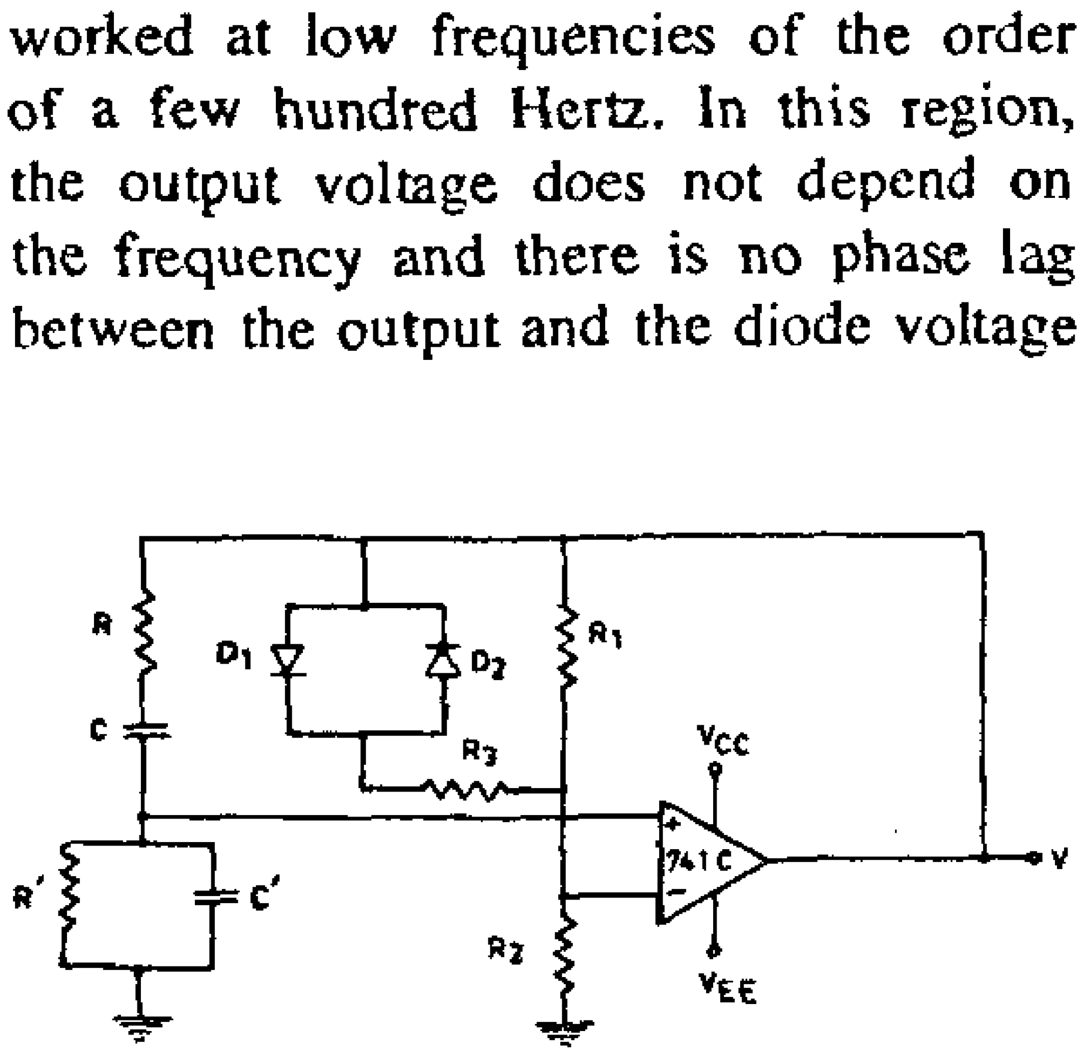

Figure 1. Circuit diagram of the Wien bridge oscillator.

drop. We have always worked with the peak voltage. Since the rate of variation of the output voltage with time is zero at the peak, the diodes spend enough time at the peak to reach equilibrium. Since $I = I_1 + I_d$,

$$\frac{V}{3R_2} = \frac{2V}{3R_1} + \frac{\left(\frac{2V}{3} - V_d\right)}{R_3},$$

which leads to

$$V = 3V_d \frac{R_1R_2}{2R_1R_2 - R_3(R_1 - 2R_2)} \qquad (3)$$

Eliminating V between eqs (2) and (3) we get a linear relationship

$$I_d = \frac{R_1 - 2R_2}{2R_1R_2 - R_3(R_1 - 2R_2)} V_d, \qquad (4)$$

with the slope of the line M given by

$$M = \frac{R_1 - 2R_2}{2R_1R_2 - R_3(R_1 - 2R_2)}, \qquad (5)$$

where M is solely determined by the three resistors. If the slope of the nonlinear forward characteristic of the diode be β at $V_d = 0$, then for $M > \beta$ we have a stable solution given by the intersection point of the nonlinear characteristic curve of the diode and the $V_d - I_d$ line as shown in the Figure 2. Two cases may arise:

(i) If $R_1 < 2R_2$ then

$$R_3(R_1 - 2R_2) > 2R_1R_2,$$

which leads to a non-physical situation since $R_1 - 2R_2$ is negative and we do not consider this case any further.

(ii) If $R_1 > 2R_2$ a necessary condition is

$$R_3 < \frac{2R_1R_2}{R_1 - 2R_2}. \qquad (6)$$

This shows that for the stability of the output voltage, R_3 has an upper limit for given values of R_1 and R_2. Again

$$R_3 > \frac{2R_1R_2}{R_1 - 2R_2} - \frac{1}{\beta}.$$

As β is very small lower limit of R_3 is negative. So in reality

$$0 < R_3 < \frac{2R_1R_2}{R_1 - 2R_2} \qquad (7)$$

Though we have said that R_3 has an upper limit we find oscillation even when R_3 is ∞, that is when R_3 and the diode combination have been removed from the circuit. But this is very unstable oscillation and there is no rational way of calculating the output voltage. The very purpose of R_3 and the diode combination is to stabilize the output voltage and they provide a rationale for finding that voltage as has been described above.

The experiment was performed on a breadboard with the DC supplies to the op-amp $V_{CC} = +12$ V and $V_{EE} = -12$ V. 1N4007 diodes were used for stabilization of the output. The resistances R, R' were 32.90 kΩ and C, $C' = 0.01$ μF. The calculated frequency is 484 Hz and the experimental frequency is 455 Hz. Within the uncertainty of the values of resistances and the capacitances this is a good agreement. The ambient room temperature was 305.5 K.

In Table 1, we have shown the different combinations of R_1, R_2 and R_3 and the corresponding peak voltages developed at the output of the op-amp. In the same table we have shown the corresponding values of M, V_d and I_d calculated with the eqs (5), (3) and (4) respectively. The error of M has been calculated by propagating the errors of R_1, R_2, R_3 and V which are all taken to be 1%. We have taken only those combinations of R_1, R_2 and R_3 for which the error in the slope M, was less than 10%. It is important to select data with an upper limit on the error of M, otherwise the exponential nature of the diode characteristic does not show up. We have plotted I_d as a function of V_d and shown in Figure 2. This is the typical diode characteristic curve. We have checked that this curve matches within error with the curve obtained by the usual DC method. Instead of finding the diode characteristic curve we can calculate the output voltage for a given value of R_1, R_2, R_3 if the nonlinear diode characteristic is known. By calculating the value of M we can find the intersection point of the line with the nonlinear curve graphically as shown in Figure 2. This gives V_d and we can find V, the output voltage with the help of eq. (3).

For a high value of V_d say above 0.7 V, M should be large, above $\sim 8(\text{K}\Omega)^{-1}$. Large values of M can be obtained with a large value of $R_1 - 2R_2$ that is $R_2 \ll R_1/2$. But these combinations of R_1 and R_2 make the sinusoidal trace on the CRO distorted. Measurement of too small a value of V_d say about 0.1 V also poses a problem as for such a low voltage the output of the oscillator is very small leading to a large noise pickup. In the intermediate range of voltages the

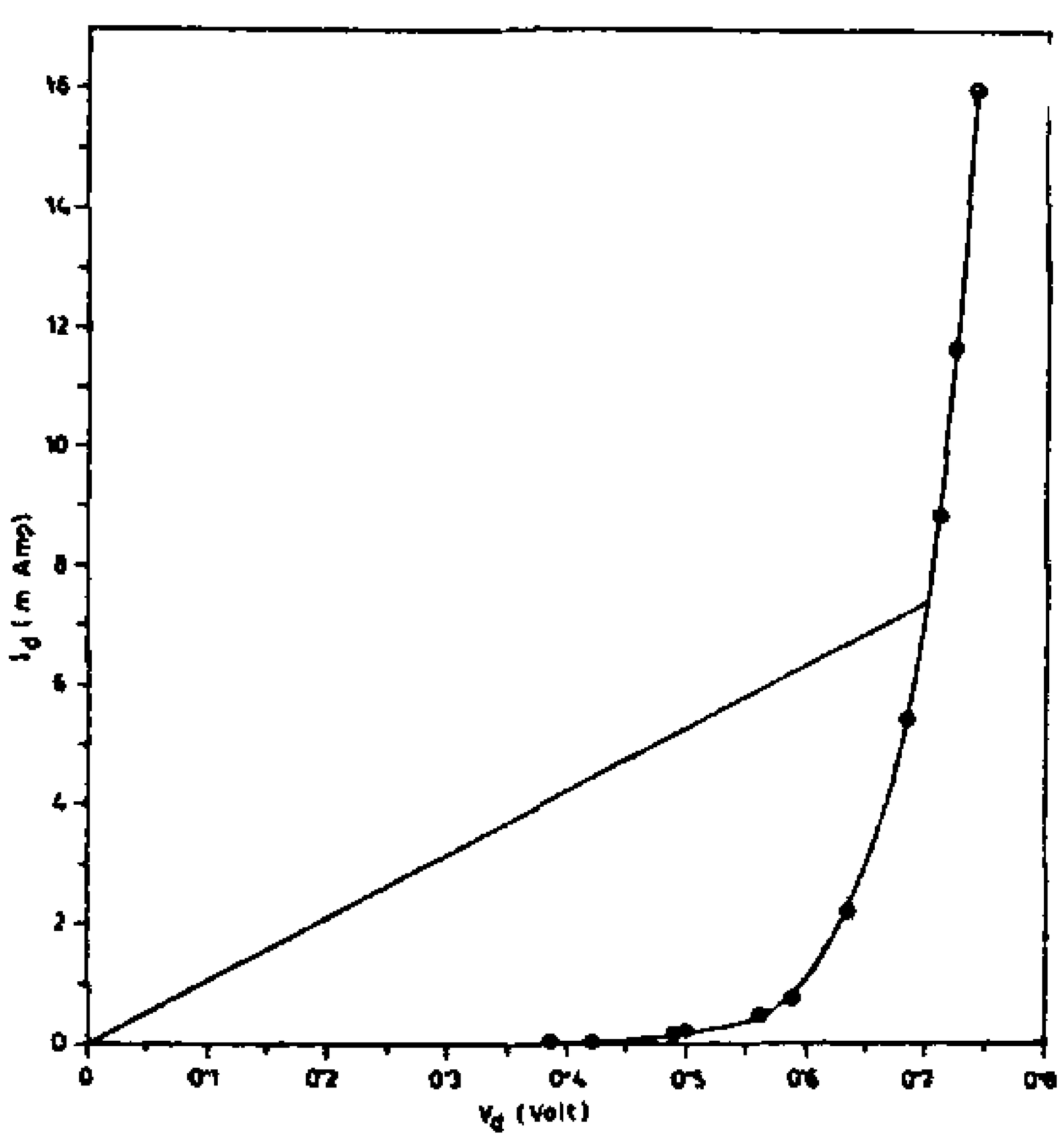

Figure 2. Stability condition of the oscillator and the characteristic curve of the diode.

Table 1. R_1, R_2, R_3 and V and the derived quantities

R_1 kΩ	R_2 kΩ	R_3 kΩ	V (peak) Volt	M $(\text{k}\Omega)^{-1}$	V_d Volt	I_d mAmp
32.91	10.070	30.17	1.385	0.05	0.387	0.02
14.76	4.694	15.40	1.567	0.10	0.421	0.04
0.8173	0.3281	0.5594	0.882	0.36	0.489	0.18
0.8173	0.3281	0.9980	1.062	0.43	0.496	0.21
4.694	0.9986	2.199	2.294	0.78	0.562	0.44
2.199	0.5593	1.468	2.499	1.24	0.592	0.73
0.8173	0.2195	0.6597	3.135	3.46	0.636	2.20
0.8173	0.1209	0.2200	2.837	8.10	0.680	5.51
4.683	0.1210	0.1756	3.408	12.57	0.709	8.90
0.8173	0.1000	0.2030	4.647	16.18	0.723	11.70
0.8173	0.1003	0.2195	6.380	21.57	0.742	16.00

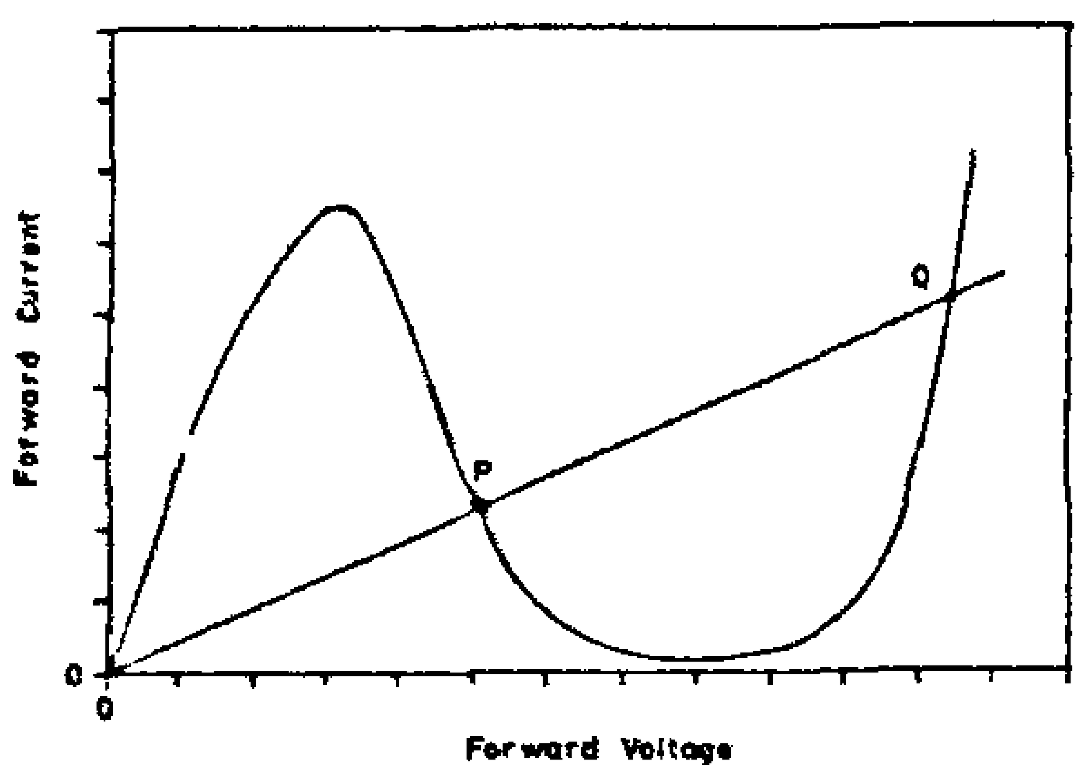

Figure 3. Forward characteristic of a tunnel diode.

measurements are quite reliable and are comparable in accuracy to the measurements obtained by the usual methods. One advantage of this method over the standard method is that here we can measure current over a wide range, spanning at least 3 orders of magnitude which is not easily available with commercial instruments.

In summary, we see that the diodes give stability to the output voltage at a given temperature and a rationale for finding it. On the other hand, if the output voltage is known we can find the diode characteristic curve. The analysis finds an important upper limit for R_3 for a given R_1 and R_2 for which the output voltage of the oscillator is stable. If instead of diodes we use tunnel diodes for the stabilization an interesting situation may arise. The tunnel diode has a characteristic as shown in Figure 3. The straight line intersects the characteristic curve at two points apart from the origin. So there is a possibility for a system with two stable solutions. This may be a very interesting subject matter for further study.

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Are sperm counts declining?

Many reports suggest that sperm counts in men have steadily declined over the last fifty years from 113 million sperms per ml in 1940 to a low of 60 million sperms per ml in 1990 (refs 1 and 2). The reason for this decline was attributed to chemical pollutants with estrogenic effects[3]. Fears have even been expressed that in the next millennium procreation may have to depend heavily on assisted reproduction. But there have been a few reports denying declining sperm counts[4,5]. What is more population figures show an upward trend specially in the developing countries. Reports on sperm counts from India appear to be scarce[6–8] and thus a confident conclusion is difficult.

Infertility Institute and Research Centre (IIRC), Secunderabad has been routinely performing semen analysis since mid-1992 adhering to the guidelines recommended by WHO. The present report is a retrospective look at the semen profiles of 1855 men who were the male partners of couples seeking treatment for infertility. These men were divided into 4 batches, A, B, C and D between August, 1993 and March, 1998 with intervals of 6, 18 and 5 months between the batches. Though the men come from a group attending an infertility clinic, the data need not be considered biased since if anything this group of men should show a decline in sperm count rather than an increase. The three other Indian studies cited also come from infertility clinics[6–8].

The fluctuating average counts in the four groups of men do not support a declining count hypothesis (Table 1). An earlier report did demonstrate a decline in sperm concentration from 69 to 43 million sperms per ml between 1992 and 1996 (ref. 7). Recently Gopalkrishnan[8] also demonstrated that sperm count in Indian men declined from 65.71 to about 30 million per ml from 1986 to 1992.

Table 1. Characteristics of semen samples from 1855 men during 1993 to 1998

	Year of semen collection			
Characteristics	Batch A August, 1993– August, 1994 ($n = 641$)	Batch B February, 1995– July, 1995 ($n = 425$)	Batch C January, 1997– July, 1997 ($n = 500$)	Batch D January, 1998– March, 1998 ($n = 530$)
Age of individual	32.3 ± 5.3^a	33.1 ± 5.5^a	32.1 ± 4.9^a	33.2 ± 5.7^a
Semen volume	2.3 ± 1.9^a	2.1 ± 1.3^a	2.2 ± 1.1^a	2.5 ± 1.4^a
Sperm concentration ($\times 10^6$ per ml)	49.8 ± 43.4^a	34.8 ± 31.0^b	53 ± 47.4^a	50 ± 43.5^a
Sperm motility (%)	47.0 ± 15.2^a	53.6 ± 19.5^a	45.5 ± 26.9^a	48 ± 23.9^a
Morphologically normal spermatozoa (%)	43.7 ± 21.5^a	29.3 ± 13.8^b	22.1 ± 16.8^c	23.9 ± 13.4^d

Values are expressed as mean ± standard deviation. Different superscripts in each line indicate that the means are significantly different ($P < 0.01$) as determined by Student's *t*-test.