noise

noise: signal you don’t want

technical noise: sources we can control in the environment ... or at least we can imagine some powerful being could control them without violating the underlying fundamental laws of physics

fundamental noise: limits set by nature via temperature, quantization, and the laws of quantum mechanics (uncertainty principle)

understand that nature sets these limits but *engineers usually do much worse*

so ... learn good engineering and to do better

thermal / Nyquist / Johnson noise

theory by Nyquist: Phys Rev 32 110 (1928)

adjacent experimental article by Johnson

applies to all devices

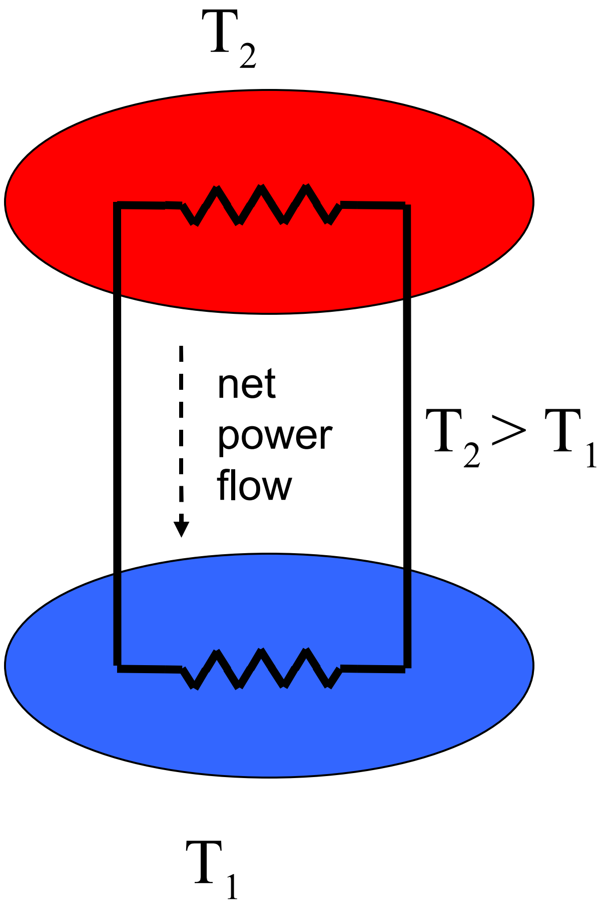
easiest to discuss for resistors, so we will …

electrons moving randomly under influence of temperature generate a fluctuating voltage

time average voltage is (of course) zero

but power (~ V^2) can be delivered to another device at a lower temperature

origin of thermal noise



- voltage fluctuations (amplitude) are greater across the hotter device
- net power flows from the hotter device to the colder device
- eventually $T_2 = T_1$

size of thermal noise

any thermodynamic system stores
(at equilibrium) ½ kT energy per DoF
bandwidth (Δf) characteristic of "receiver"

V /R = (½ kT) (Δf) (DoF/unit BW)
2 DoF for 2 directions of energy transfer
2 DoF for electric + magnetic fields
2 DoF for arbitrary polarization direction
gives 2 x 2 x 2 = 8 states

$$|V_n| = \sqrt{4kT\Delta f R}$$

$$\left|V_n\right| = \sqrt{4kT\Delta f R}$$

at room temperature kT ≈ (1/40) eV

e ≈ 1.6 x 10^{-19} coulomb/electron

so 4 kT ≈ 0.1 x 1.6 x 10^{-19} coulomb-volt

say Δf ≈ 300 kHz

(e.g., an FM radio station)

say R = 100 MΩ

(e.g., an inexpensive digital voltmeter)

$V_n \approx (10^{-1}\ \ 1.6\text{x}10^{-19}\ 3\text{x}10^{5}\ 10^{8})^{1/2}$

$\approx 7\text{x}10^{-4}$ volt

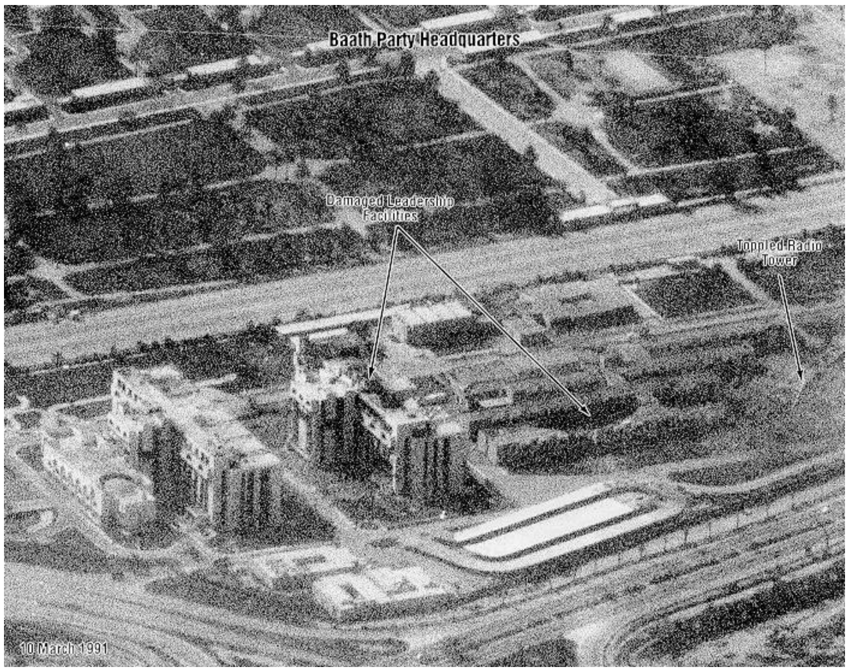
so RMS noise voltage ≈ 1 mV

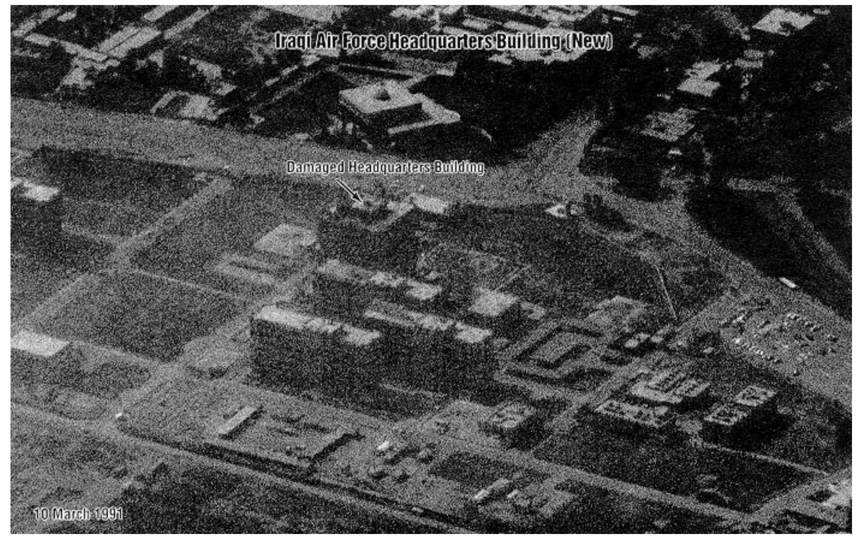
assignment

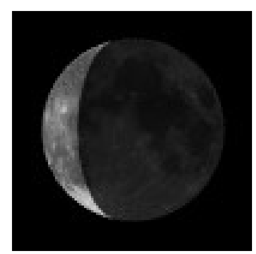
8) An inexpensive modern oscilloscope might have a signal bandwidth of 100 MHz; a typical pyroelectric “warm body sensor” has an output impedance around 100 MΩ; what RMS noise voltage would you expect to see at room temperature, at 30 K, and at 3000 K?

shot noise

statistical fluctuations in current originating with the quantization of electronic charge







moon phase
1991 Mar 10

current and electrons

current is not a continuum fluid … it is composed of a stream of individual electrons

when the current is small … or the sampling time is short … a typical sample may contain a relatively small number of electrons

the current corresponding to few thousand electrons/second is visible to a modern analog current measuring instrument

statistical fluctuations from sample-to-sample are then apparent as “shot noise”

I ampere = I coulomb/second

dN/dt = I/e (coulomb/s)/(coulomb/electron)

e = 1.602 10   coulomb/electron

(I/e) Δt = N electron (seen in Δt seconds)

ΔN = (I Δt/e) (*standard deviation* of the distribution of the values seen for N)

ΔI = e ΔN/Δt (*standard deviation* of the distribution of the observed values of I

ΔI = (e/Δt) (I Δt /e) **= (I e / Δt)$^{1/2}$**

but what to use for Δt ?

surely it depends on 1/bandwidth,

but how exactly?

the "Nyquist sampling theorem"* says

that the right numerical factor is 1/2

so need to sample for $\Delta t = (2\ BW)^{-1}$

so $\Delta I = (I\ e\ /\ \Delta t)^{1/2} \rightarrow (2\ BW\ e\ I)^{1/2}$

if BW = 100 kHz and I = 10 mA then

$\Delta I \approx 18$ nA, about 2 ppm of the signal

* you can reconstruct a continuous function perfectly from discrete samples at ≥ 2x its highest Fourier frequency

assignment

9) What is the magnitude of the shot noise you would expect to see on a current measured at the highest sensitivity setting of a typical modern picoammeter in bandwidth 100 kHz?
(do a web search for “picoammeter” to find the specifications of a modern off-the-shelf commercial instrument)

1/f noise

it is observed that noise power-per-unit-bandwidth increases with decreasing frequency, i.e., $1/f^{n}$, $n \sim 1$

called “pink” noise, in contrast to “white” noise character of Johnson and shot noise

its origin is still an active research topic: quantum mechanics, uncertainty, chaos, etc

but the phenomena is certainly ubiquitous and probably universal

to read more about 1/f noise:

A Bibliography on 1/f Noise

Last modified on: December 17, 1999, by wentian*li of rockefeller university

---

1/f noise ("one-over-f noise", occasionally called "flicker noise" or "pink noise") is a type of noise whose power spectra *P(f)* as a function of the frequency *f* behaves like: $P(f) = 1/f^a$, where the exponent *a* is very close to 1 (that's where the name "1/f noise" comes from).

If we mix visible light with different frequencies according to 1/f distribution, the resulting light may be pinkish (that's what other people says, I've never done an experiment to confirm it though!) Mixtures using other distributions should have different colors. For example, if the distribution is flat, the resulting light is white (so noise with *P(f)=constant* power spectra is called "white noise") [see also, colors of noise].

1/f noise appears in nature all over the places (a frequently-used word to describe this situation is "ubiquitous"). This bibliography is an attempt to show this fact.

Let me classify the publications on 1/f noise by the following categories:

- General References
  - General Review of 1/f Phenomena [10 entries]
  - Conference Proceedings on 1/f Noise
- Universal Aspects of 1/f Noise
  - Models and Theories of 1/f Noise [35 entries]
  - Mathematical and Statistical Properties of 1/f Noise [33 entries]
  - 1/f Noise in Dynamical System Models [17 entries] **updated**
- Specific Examples of 1/f Noise
  - 1/f Noise in Electronic Devices [107 entries] **updated**
  - 1/f Noise in Electronic Devices: MOS [49 entries] **New!**
  - 1/f Noise in Electronic Devices: Reviews and Models [17 entries]
  - 1/f Noise in Ecological Systems [13 entries] **updated**
  - 1/f Noise in Heartbeat [11 entries]
  - 1/f Noise in Biology (Miscellaneous) [11 entries] **updated**
  - 1/f Noise in Network Traffic [9 entries]
  - 1/f Noise in Traffic Flow [8 entries]
  - 1/f Noise in Music and Speech [7 entries]
  - 1/f Noise in Neuro Systems [7 entry]
  - 1/f Noise in Granular Flow [7 entry]
  - 1/f Noise in Astronomy [6 entries]

http://www.nslij-genetics.org/wli/1fnoise

assignment

10) Browse the given website on 1/f noise, select a subtopic and an article from the list "Specific Examples of 1/f Noise", browse the article (or even just the abstract, if it is detailed enough: state the citation), and summarize what you read in ~ ½ page. Mention *at least*: is the method theoretical, computational, or experimental? what is the observation that exhibits 1/f noise? how close to 1 is the observed exponent?