UiO : Department of Informatics
University of Oslo

IN5230
Electronic noise –
Estimates and countermeasures

Lecture 11 (Mot 8)

Sensors – Practical examples

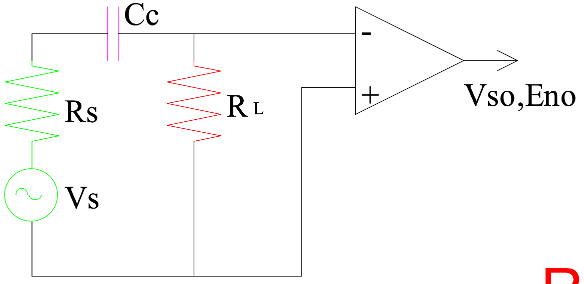
- Six models are presented that "can be generalized to cover all types of sensors."
- Naming:
  - Sensor: All types
  - Transducer: Energy from one form to another
    - Eg radiation ⇒ Power
    - Piezo electric element (bidirectional function): Motion ⇔ Voltage
    - Transducer = Sensor + Actuator
  - Detector: Optics, Infrared, Particle
- Simulators model the most common types of noise while special noise types such as GR (Generation-Regeneration noise) must be represented by separate (typically user defined) noise models.

8-1 Voltaic Sensor

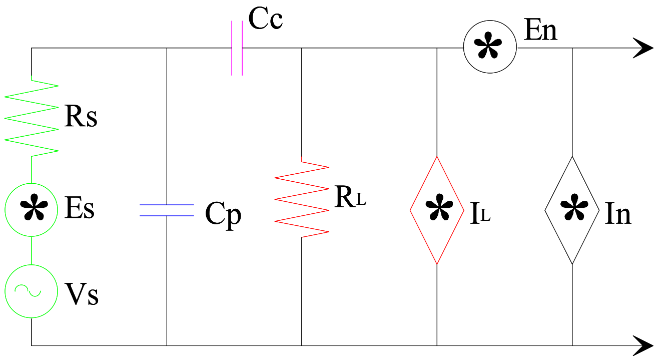
This type of sensor generates a voltage signal.

Sensors:

- Thermo coupler
- Thermopile
- Pyro electric infrared detector



RED



C_C: Because we are only interested in the AC portion of the sensor signal.

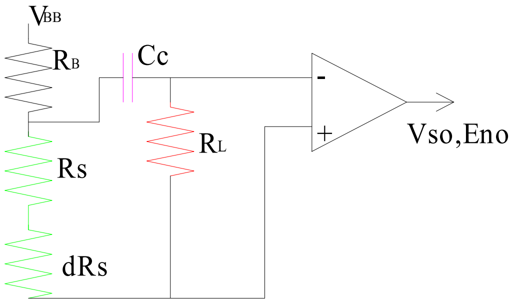
R_L: Provides bias to the amplifier and any impedance matching.

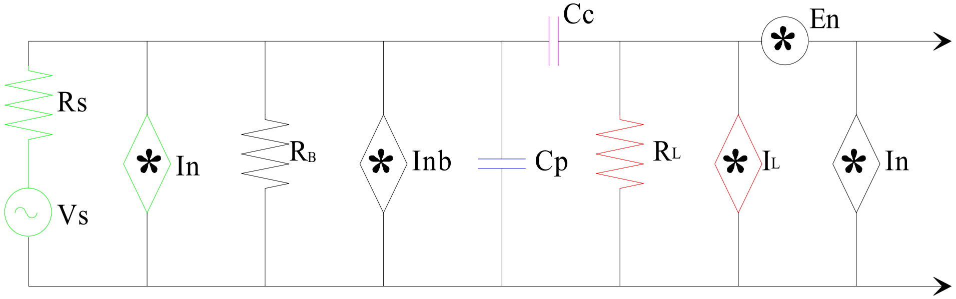
C_p: Parasitic capacitance of the sensor or between the connection lines.

Low noise $\Rightarrow$ R_L should be large, C_p should be small and C_C large.

The amplifier should be chosen so that $R_0=R_S$ and E_nI_n is as small as possible.

8-2 Biased resistive sensor





Yellow

For this type of sensors, the resistance will change somewhat with what is being measured. ($dR_S \ll R_S$).

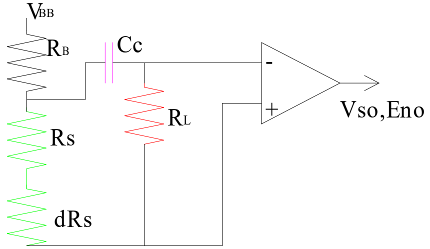
A bias network is required. Two new noise sources have to be considered: V_{BB} and R_B.
If the sensor resistance is placed in a bridge, there will also be contributions from the other bridge resistors.

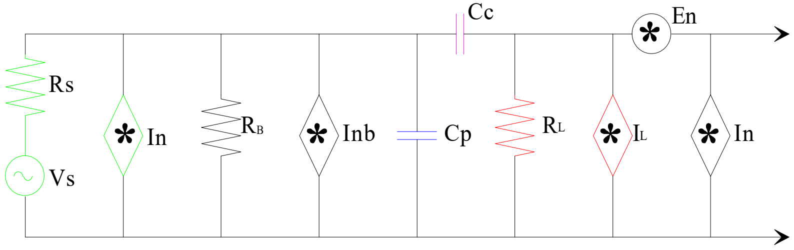
Sensors:

- Stretch lap (Strain gauge)
- Photo conductive infrared cell
- Bolometer radiation detector
- Resistive thermometer
- Piezo resistive sensors

R_B: Sets sensor bias
C_C: Removes DC-signal
R_L: Sets amplifier input bias

$$V_S = I_B \Delta R_S \cong \frac{V_{BB}\Delta R_S}{R_S + R_B}$$





Alternatively the signal is modelled as a current source in parallel with R_S: $I_S=V_S/R_S$ (not shown here).

I_{ns}: (Incorrectly named I_n in parallel with Rs in the figure)

- Thermal noise
- 1/f-noise
- G-R noise (Generation-Recombination)

I_{nb}: Thermal noise and any other noise due to R_B.

Low noise $\Rightarrow$ R_B should be large. R_B may be replaced by a coil. C_C should be so large that I_nX_c does not contribute even at the lowest frequencies.

If V_{BB} can not be changed R_B has to be selected as a compromise to get high enough V_S and low enough noise. The proper choice depends on the sensor characteristics. If V_{BB} can be increased, it is possible to achieve both high gain and low noise. Further we should have $R_L \gg R_S$ so that I_L does not contribute significantly.

8-3 Optoelectronic Detector

Applications:

- Infrared detection
- Heat metering
- Light and colour measurement
- Fibre optic sensors
- Sensors for CDs
- Laser detectors

Two types:

1. Photovoltaic: Light provides a voltage on output
2. Photoconductive: Light provides current (in addition to dark current). A bias is required to collect charges.

Photo conductive detectors have two subgroups:

2a. Made of bulk semiconductor material and where the conductivity increases with exposure. Modelled as a variable resistance. Discussed earlier.

2b. Perceive the detector as a diode. The diode is reverse biased.

<u>In the following we will discuss a photo conductive diode of type 2b (i.e. with a diode model of the sensor)</u>

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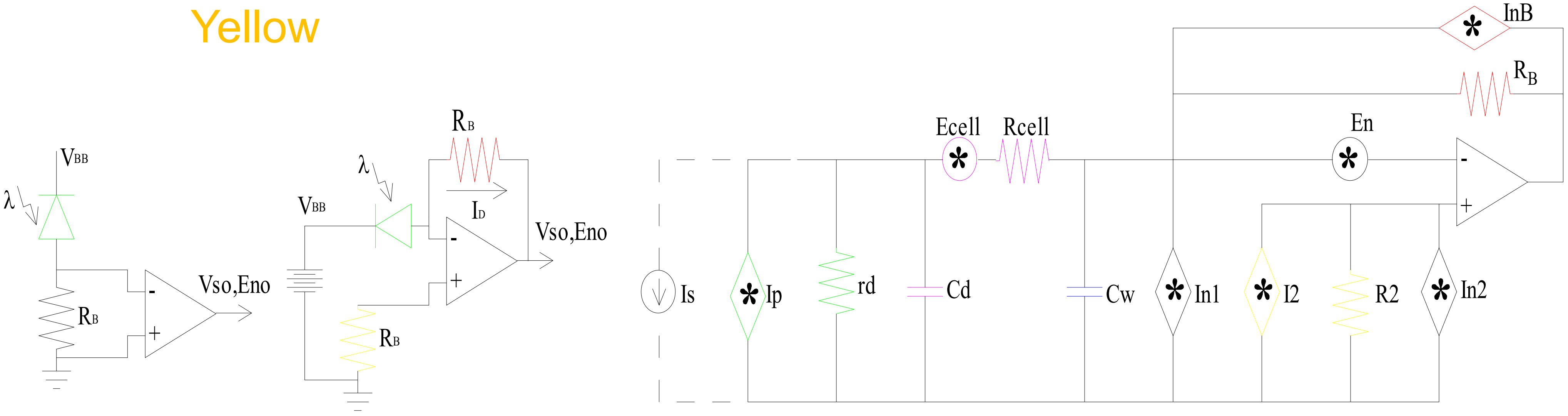
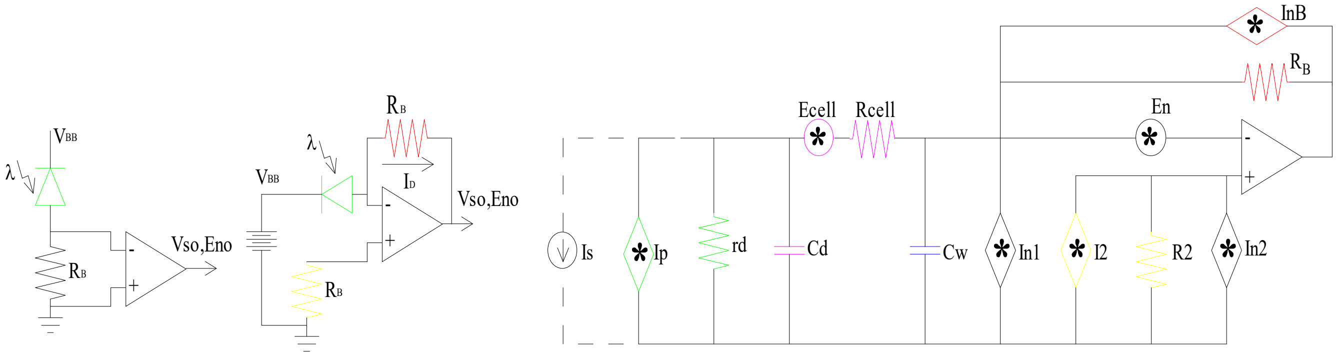


(Figur fault: Yellow R_B should be R_2. Cd, Ecell and Rcell should all have been green (part of sensor diode).)

The figure shows three schematics: The simple schematic, the most used schematic and the noise form of the most used schematic.

The voltage over *R_B* is a product of *R_B* and the current through the detector:

Current = leakage current + signal current.



R_B provides a virtual ground at the input that will reduce the input impedance and thus improve the frequency response. $V_0=-I_D R_B$.

I_S: Signal current (not noise current)
I_P: Diode noise in the detector (not thermal noise)

$$\left(I_{sh}^2 + I_{G-R}^2 + I_{1/f}^2\right)^{1/2}$$

r_d: Dynamic noiseless resistance in the photo diode
C_d: Parasitic capacitance of the diode
R_{cell}: Series resistance of the diode
E_{cell}: Thermal noise in the diode
C_W: Parasitic capacitance of the wires
R_B: Feedback resistance
$I_n B$: Thermal noise in R_B
R_2: Resistance on the positive amplifier input
I_2: Thermal noise in the R_2
E_n, $I_n 1$ and $I_n 2$: Noise in the amplifier model.

FET input at the amplifier is probably the best choice here!

8-3-1 Photo Diode Noise Mechanisms

(All noise currents passing through the diode)

$$I_p = \left(I_{sh}^2 + I_{G-R}^2 + I_{1/f}^2\right)^2$$

$$I_{sh}^2 = 2qI_D\Delta f$$

$$E_{cell}^2 = 4kTR_{cell}\Delta f$$

$$I_{ns} = E_{cell} / R_{cell}$$

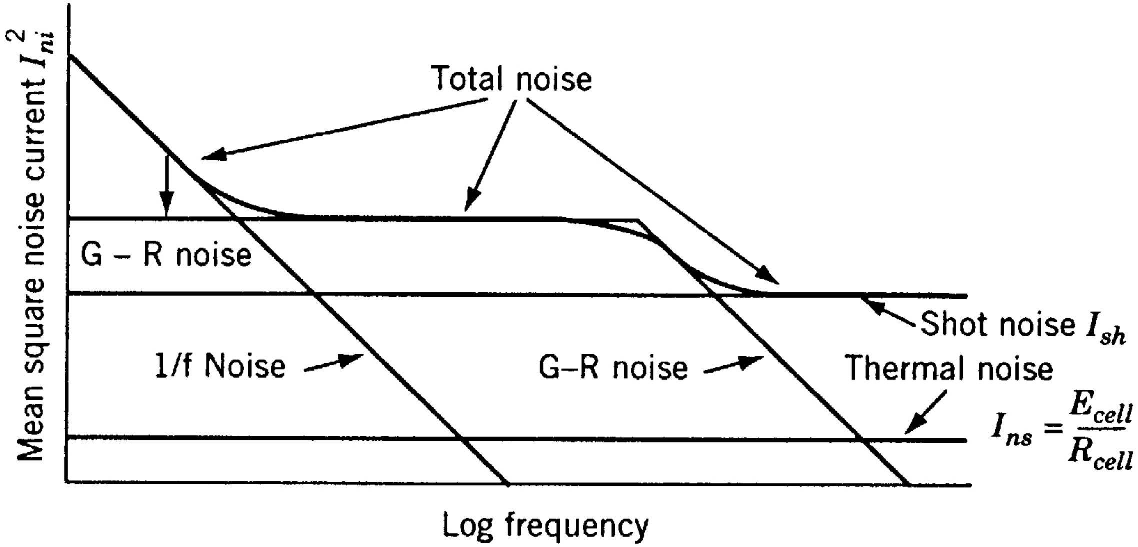


Figure 8-8 Noise sources in a photodiode.

- I_{G-R}: Generation-Recombination noise. The conductivity varies due to the variations in the free charge. The noise is "White" until 1/(average life time of the e-h-pairs in the detector diode).
- I_{sh}, I_{G-R} and $I_{1/f}$: Function of current and increases with current strength. Minimum noise when the current through the diode is only background photo noise.

NEP = Noise Equivalent Power

... ... is the value of an input signal (in this case the light power) that produces an electrical output signal that is as large as the output noise alone when there is no input signal.

8-3-2 PIN Photo Diode Sensor

PIN diode is used for visible light and to the portion of the infrared spectrum that is closest to visible light. PIN=P - Intrinsic/non-doped - N. The intrinsic region gives a larger depletion/sensitive region.
Need bias voltage <50V and typically in the range 5-20V.

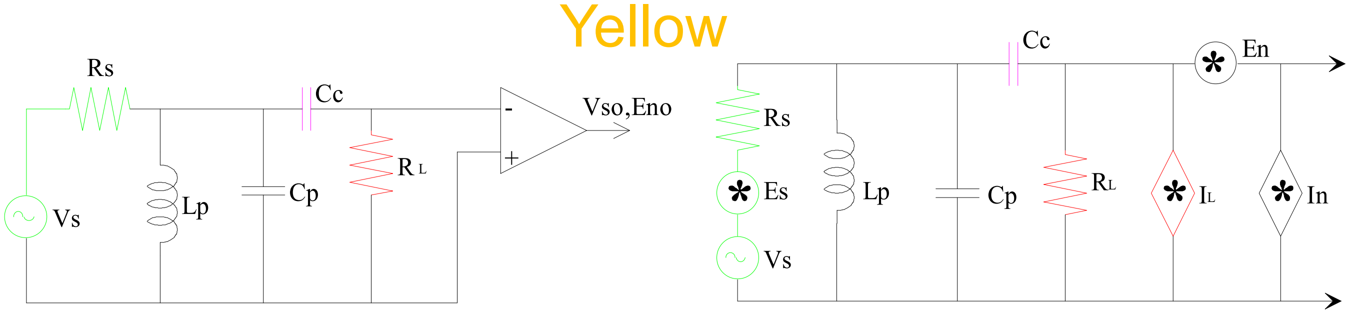
Example values:

- V_B=20V
- C_d= typically 1pF-5pF
  R_{cell} = <50Ω
- R_d=10GΩ
- I_D: Dark current: 100pA typical + reverse current
  1/f-noise: Noise corner: 20 - 30 Hz
  - 10dB/dec increase below corner frequency

Max response: 0.5μA/μW in the visible frequency band 0.5-0.8μm, 0.75 electron/photon=75% quantum efficiency

NEP down towards -110dBm/√Hz

8-4 RLC Sensor Model



Sensors:

- Heads for magnetic tapes
- Inductive pick-ups
- Dynamic microphones
- Linear variable differential transformers
- “Various other inductive sensors"

R_S: Sensor series resistance or the real part of the sensor impedance.

E_S: Thermal noise in R_S

L_P: Sensor inductance

C_P: Capacitance used to decide the resonance. It consists of internal and external parasitic and intended capacitances.

C_C: Isolate the DC-component from the amplifier so that it can be set up with the desired bias voltage.

I_L: Thermal noise in R_L

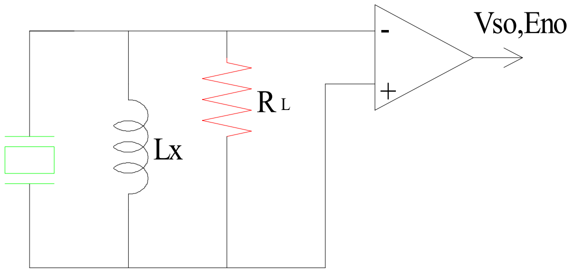
Low noise ⇒ At resonance E_n will be at its minimum, and I_n will only be dependent on the impedance of the series inductance and resistance. (Eq. 7-13)

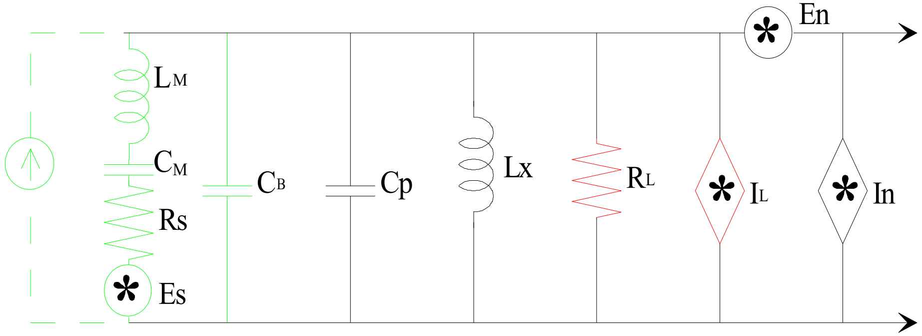
Coils with magnetic core have decreasing inductance and growing resistance at higher frequencies. It may therefore be necessary to model the coil at several frequencies.

Construction of the sensor coil and resonance capacitance can be done so that maximum S/N ratio is achieved.

V_S is proportional to the number of turns.
Coil resistance is proportional to the number of turns for small diameters. Noise is proportional to the square root of the number of turns. Thus, the signal level will increase more than the noise level with increasing number of turns until a certain limit.

8-5 Piezoelectric Transducer





Yellow

Two resonances

--- Series resonance L_M and C_M

--- Parallel resonance (C_M+C_B) and L_x.

Normally the parallel resonance is preferred

L_M: Mechanical inductance

C_M: Mechanical capacitance

R_S: Serial loss in the transducer

E_S: Thermal noise in R_S

C_B: Transducer capacitance

I_S: Signal current (No noise)

C_p: Parasitic cable capacitance

L_x: External coil

R_L: Load resistance

I_L: Thermal noise in R_L

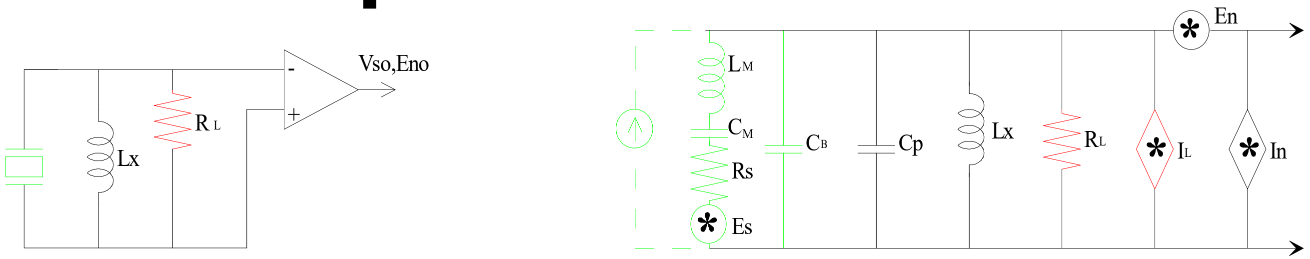
"Piezo" ⇔ "Electric"

Mechanical motion ⇔Electrical response

Applications:

- Microphones
- Hydrophones
- Sonar
- Seismic detectors
- Vibration Sensors
- Accelerometers

Equivalent input noise:



$$E_{ni}^2 = 4kTR_S + E_n^2\left(\frac{Z_S + Z_L}{Z_L}\right)^2 + \left(I_n^2 + I_L^2\right)Z_P^2$$

Z_S: The serial impedances of R_S, C_M and L_M.

Z_L: The parallel impedance of C_B, C_P, L_x and R_L.

Z_P: is $Z_S || Z_L$

R_S is typically small and the first term can usually be ignored. This is a high impedance system and E_n will be small compared to I_n. To get the least amount of noise current should R_L be large and I_n small.

An FET amplifier should be chosen due to:

- Small I_n
- R_L can be made be very large

8-6 Transformer Model

Why having a transformer between the sensor and the amplifier?

1) Impedance matching makes that both the sensor and the amplifier "sees" the impedance with the least noise.

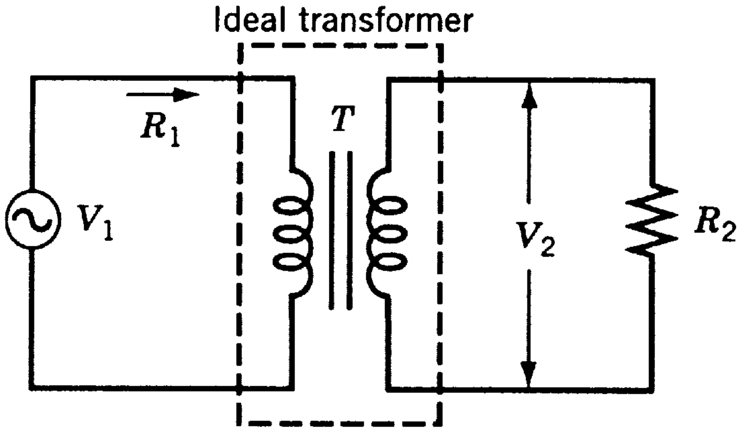
2) Provide insulation between the source and amplifier. (Security, DC-currents, etc.)

3) To achieve maximum transfer of signal power.

4) Most optimal for the smallest sensor resistances

However the transformer also contributes with some noise!

Impedance transformation



- Assume ideal transformer:

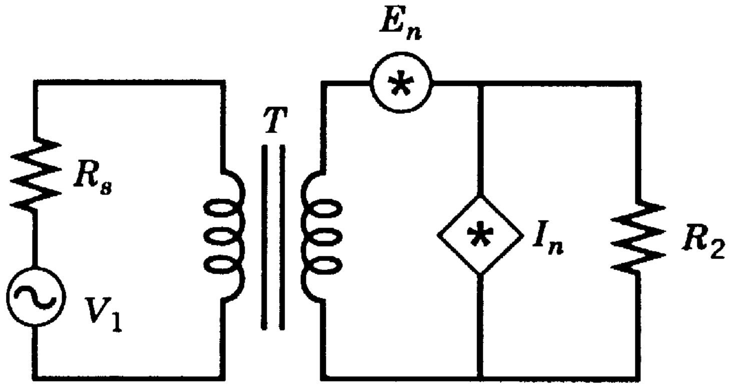
$$P_p = P_s \Rightarrow \frac{V_1^2}{R_1} = \frac{V_2^2}{R_2}$$

$$Def : T = \frac{N_S}{N_p} \quad V_2 = TV_1$$

- We will then get

$$R_1 = \frac{R_2}{T^2}\left(= R_2 \frac{N_p^2}{N_s^2} \right)$$

In this way the sensor resistance is transformed so that the amplifier “sees” the optimal source resistance giving the least possible noise.



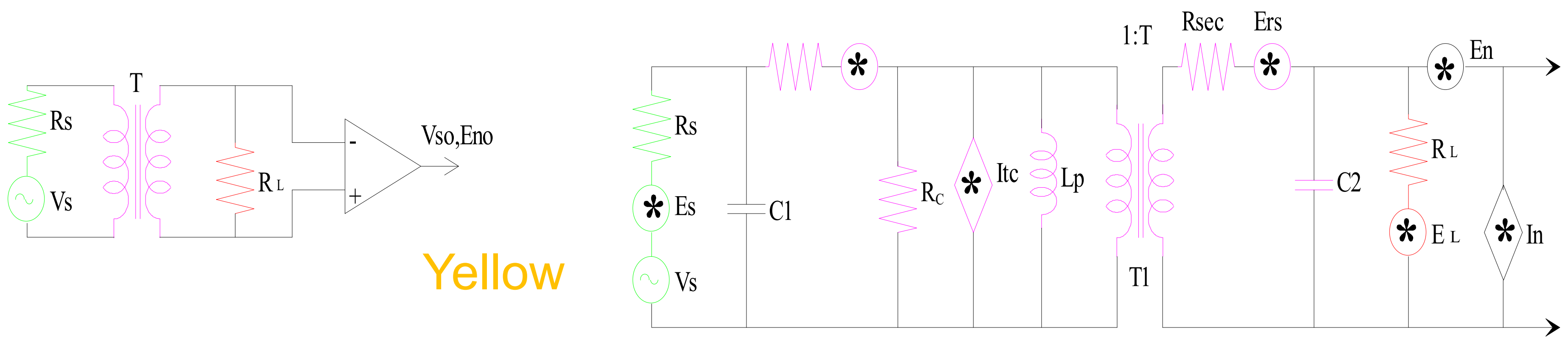
We have previously defined $R_0=E_n/I_n$. When we let $E_{n'}$ and $I_{n'}$ represent their transferred value on the source side we get:

$$E'_n = \frac{E_n}{T} = E_n \frac{N_p}{N_s} \quad \text{and} \quad I'_n = TI_n = I_n \frac{N_S}{N_P}$$

We will then have on the source side:

$$R'_0 = \frac{E'_n}{I'_n} = \frac{E_n}{T^2 I_n} = \frac{R_0}{T^2} = R_0 \frac{N_S^2}{N_P^2}$$

We match so that $R'_0=R_S$ and have $R_S=R_0/T^2 \Rightarrow T^2=R_0/R_S$. We choose the turn ratio of the transformer so that $T^2=R_0/R_S$ to get the smallest possible noise.



V_S: Sensor signal voltage

R_S: Sensor resistance

E_S: Thermal noise in R_S

C_1: Primary shunts capacitance

R_P: Resistance primary side of transformer, serial (not named in figure)

E_P: Thermal noise in R_P (not named in figure)

R_C: Resistance primary side of the transformer, parallel

I_{tc}: Thermal noise in R_C

L_p: Inductance at the primary side

T_1: Noiseless, ideal transformer

R_{sec}: Resistance secondary side of transformer

E_{rs}: Thermal noise in R_{sec}

C_2: Secondary shunts capacitance

R_L: Load resistance

E_L: Thermal noise in R_L