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Volume 05

Calculating Filters



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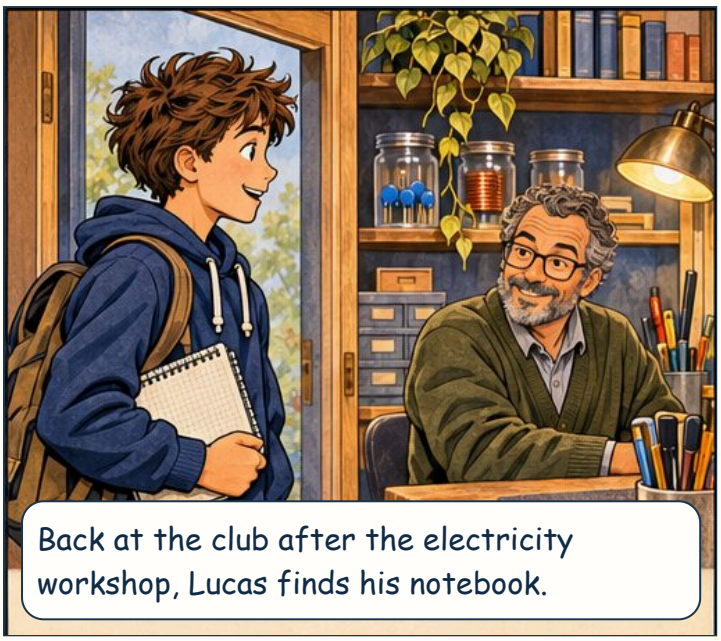
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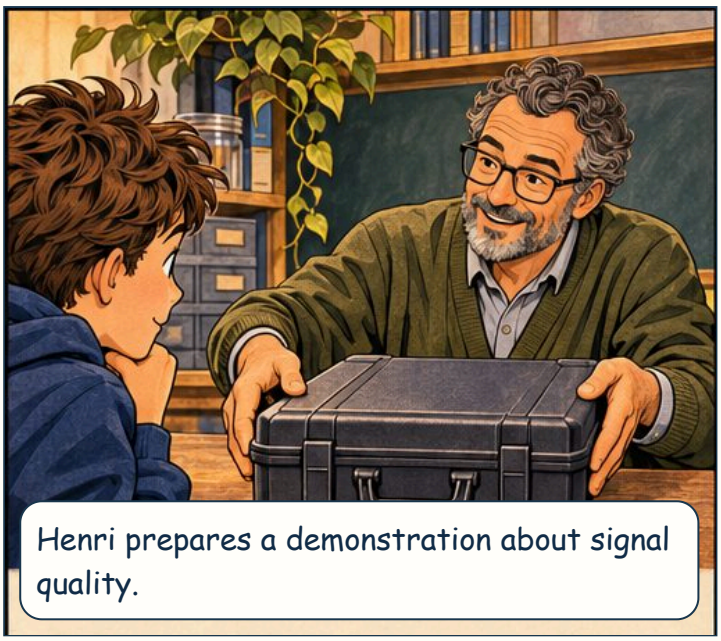
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Illustrations created with assistance from artificial intelligence.

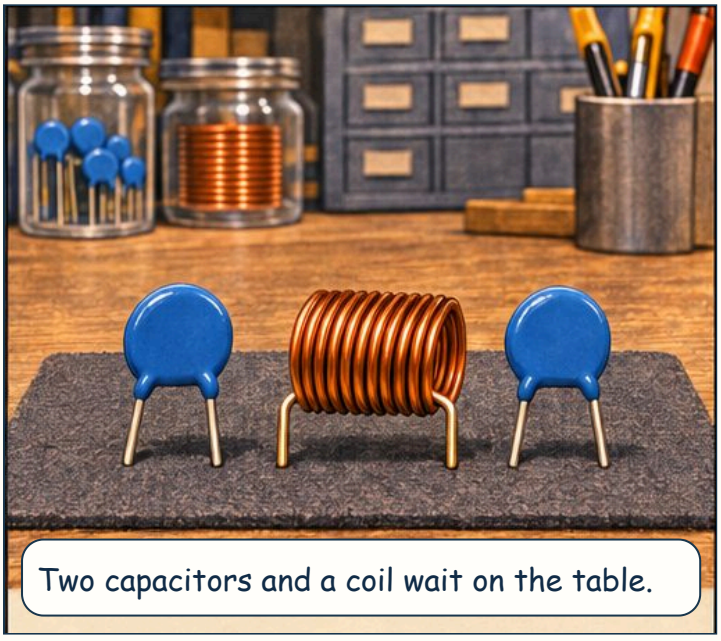
A new mission



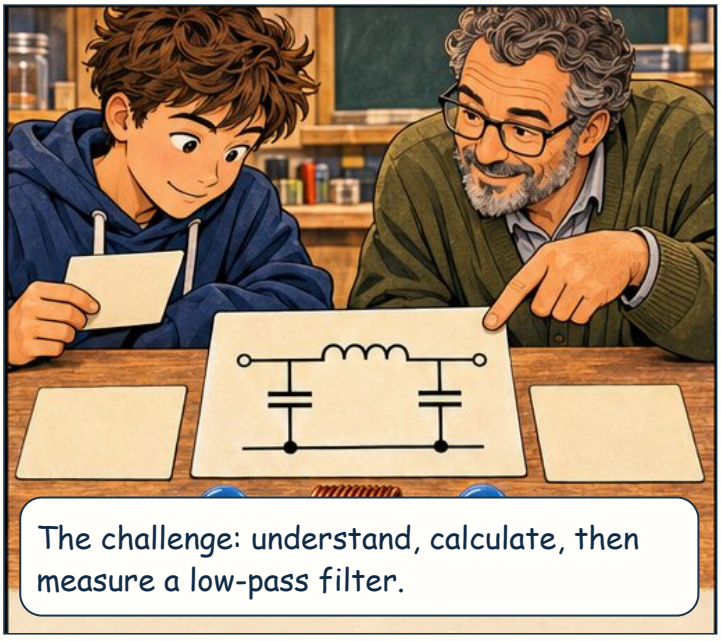
Back at the club after the electricity workshop, Lucas finds his notebook.



Henri prepares a demonstration about signal quality.



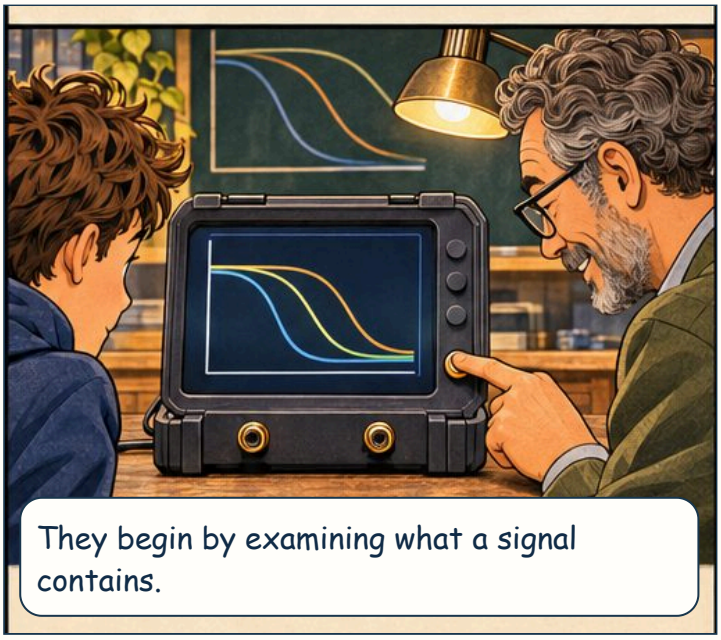
Two capacitors and a coil wait on the table.



The challenge: understand, calculate, then measure a low-pass filter.

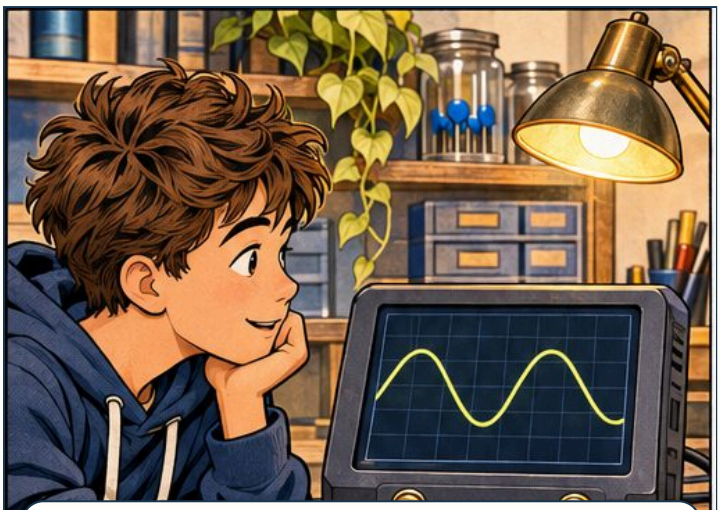


The youngster wonders how three components can change everything.

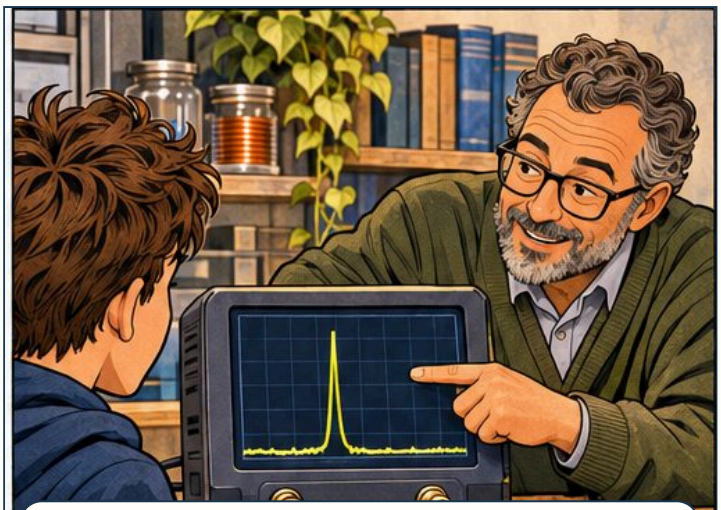


They begin by examining what a signal contains.

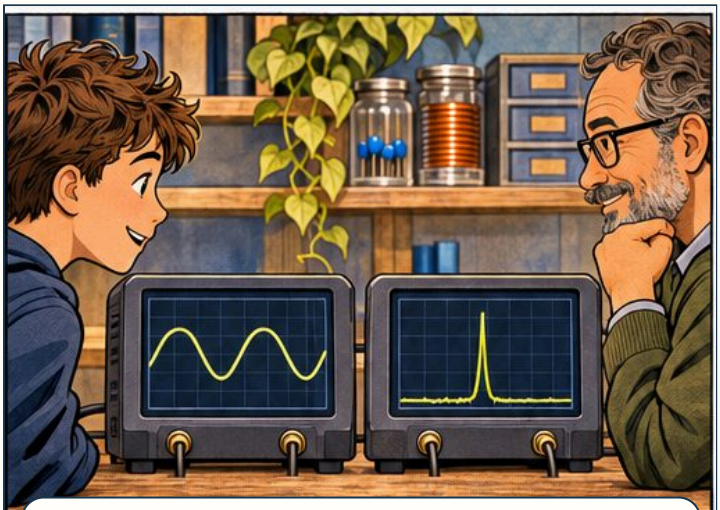
The signal and its portrait



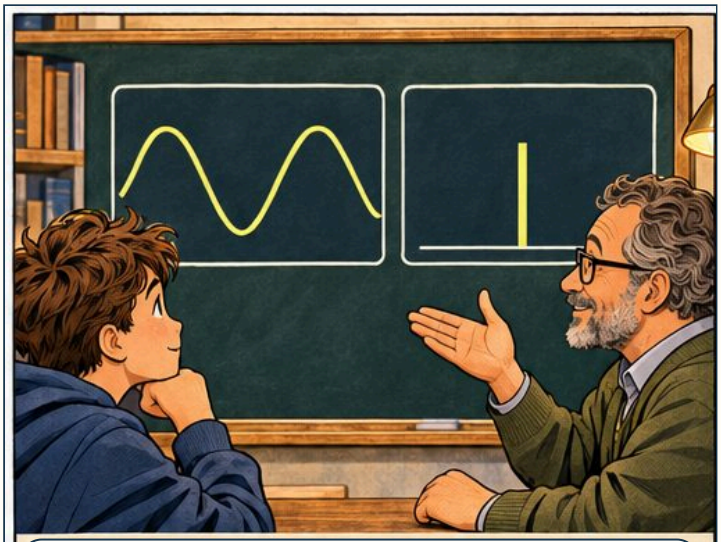
A time-domain curve shows how a signal changes.



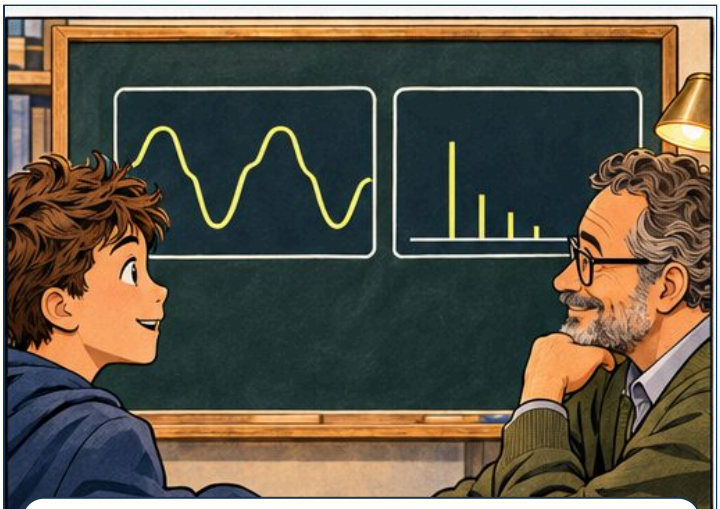
A spectrum displays its components by frequency.



Both views describe the same signal differently.



An ideal sine wave has just one frequency.

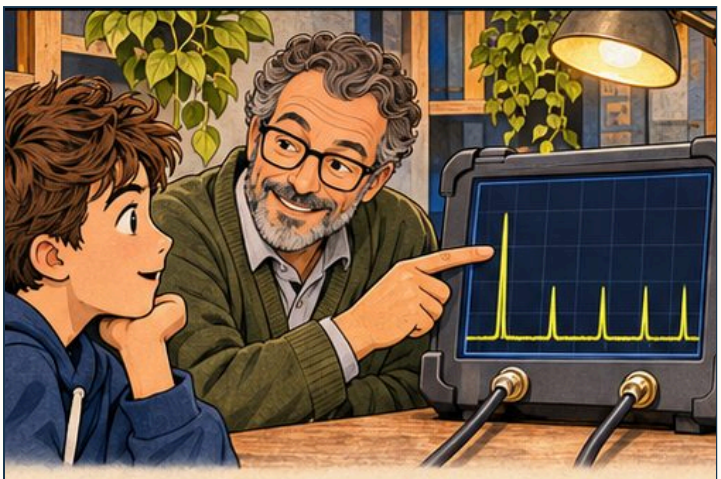


A distorted waveform may contain several components.



The youngster discovers a portrait he could not read before.

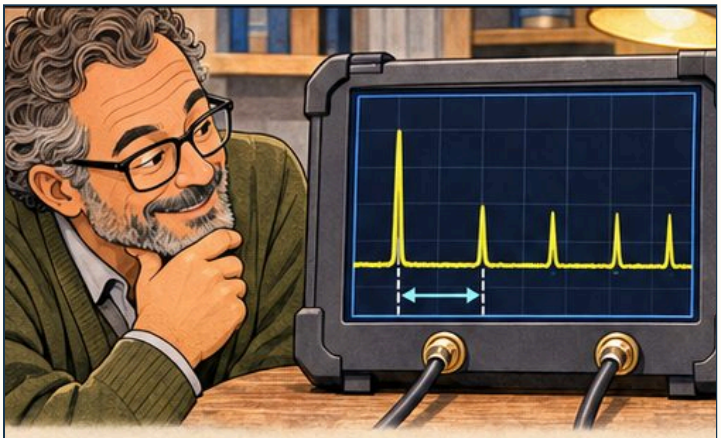
Harmonics revealed



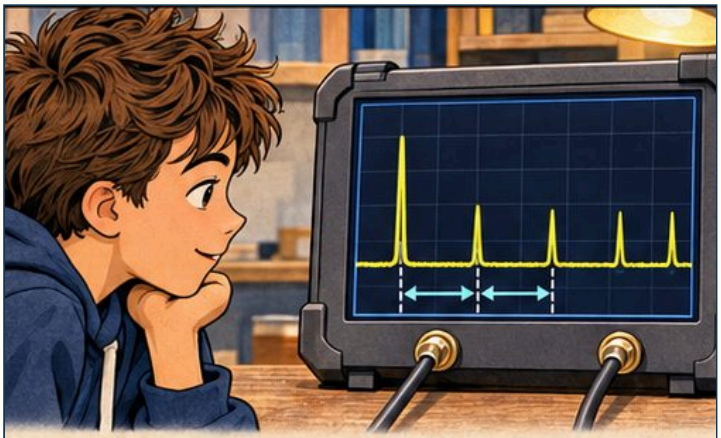
The fundamental frequency provides the first reference for a periodic signal.



Its harmonics are integer multiples of that frequency.



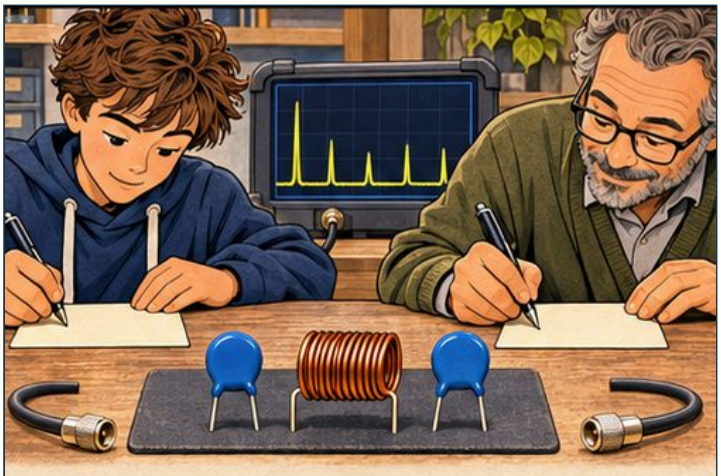
The second harmonic is twice the fundamental.



The third is three times that frequency.

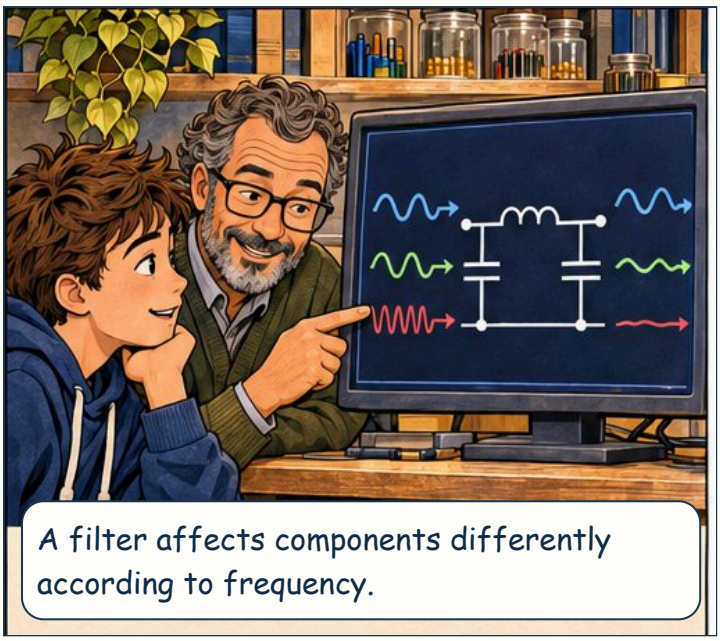


Not every unwanted component is a harmonic, though.

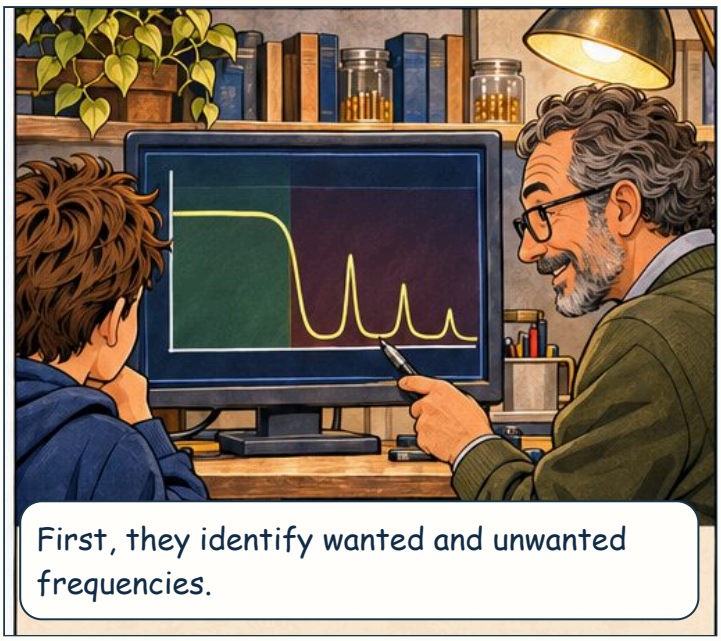


The filter must meet a precisely defined need.

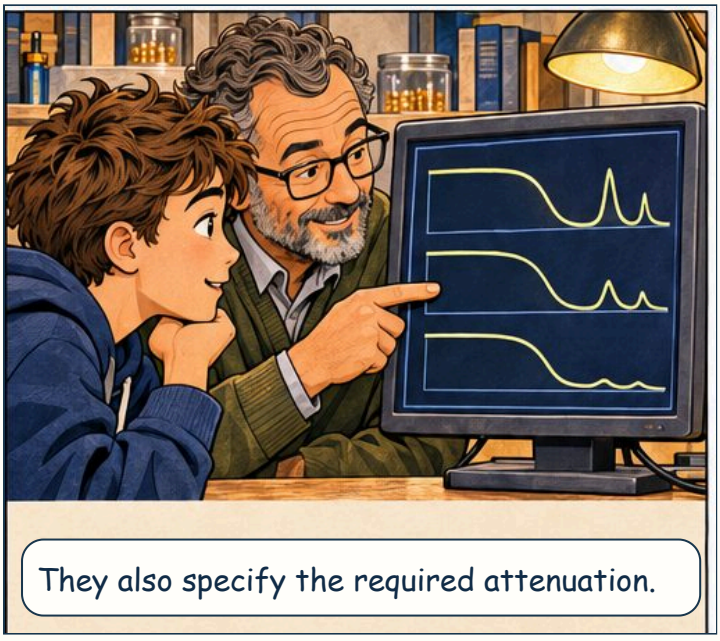
Choosing what to keep



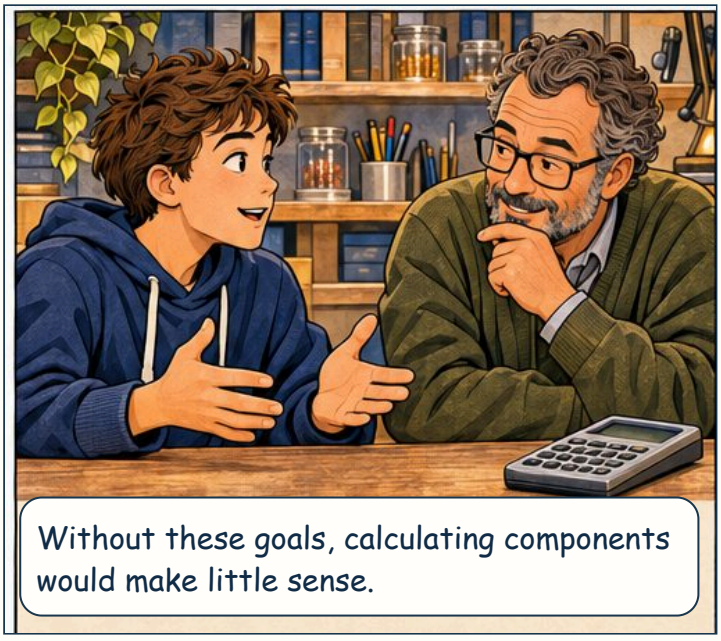
A filter affects components differently according to frequency.



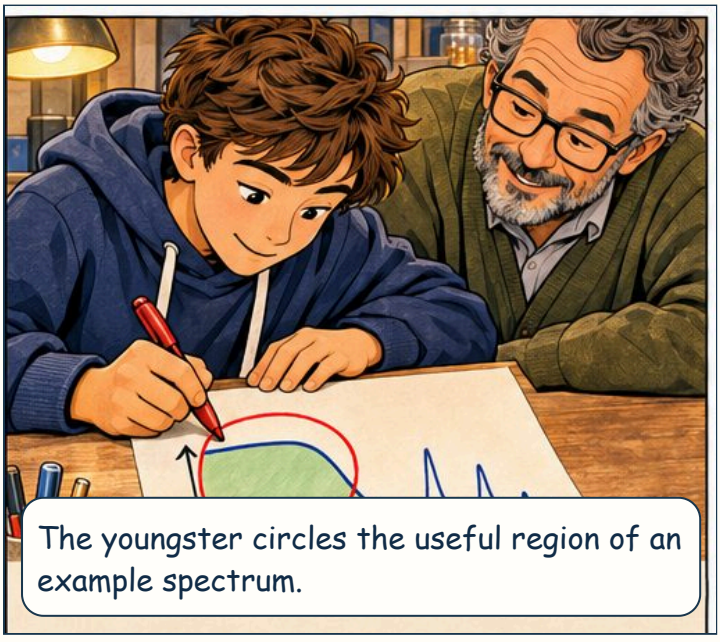
First, they identify wanted and unwanted frequencies.



They also specify the required attenuation.



Without these goals, calculating components would make little sense.

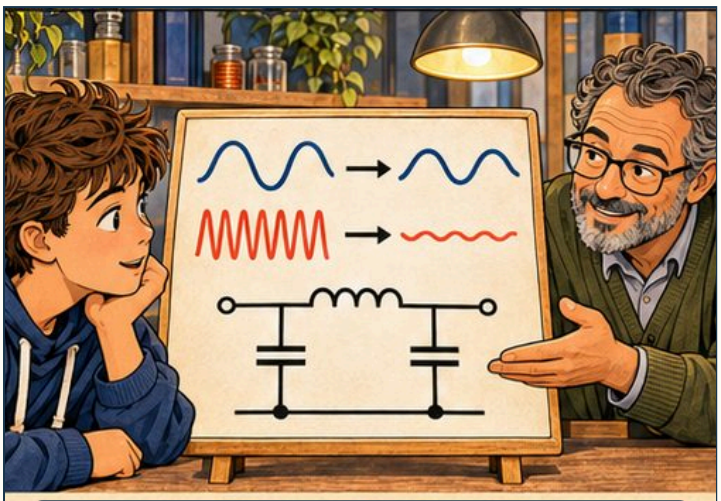


The youngster circles the useful region of an example spectrum.



His notebook becomes a design specification.

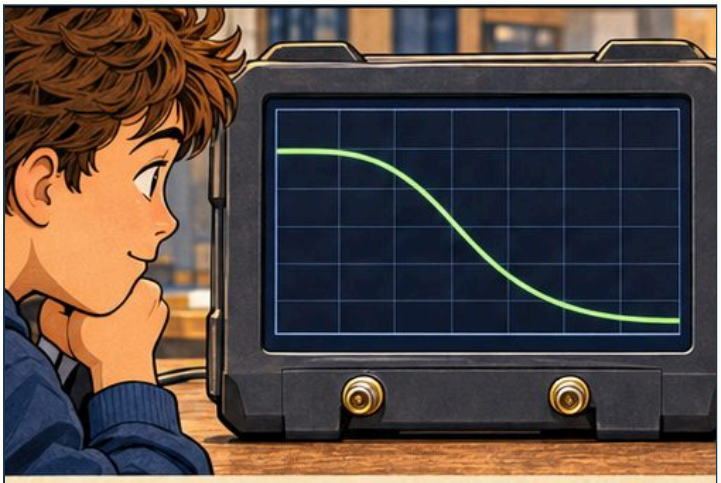
Choosing a low-pass filter



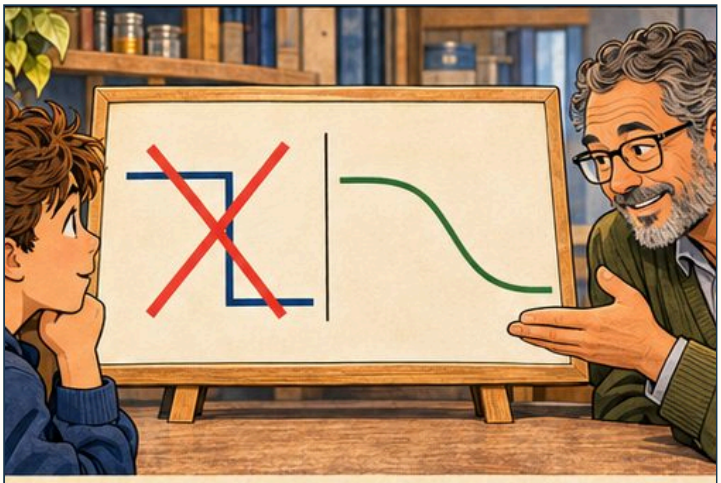
A low-pass filter passes low frequencies better than high ones.



Its passband lies on the low-frequency side.



Higher up, attenuation increases gradually.



A real transition is never a perfect vertical wall.



This type suits today's demonstration.



The youngster draws a slope rather than a barrier.

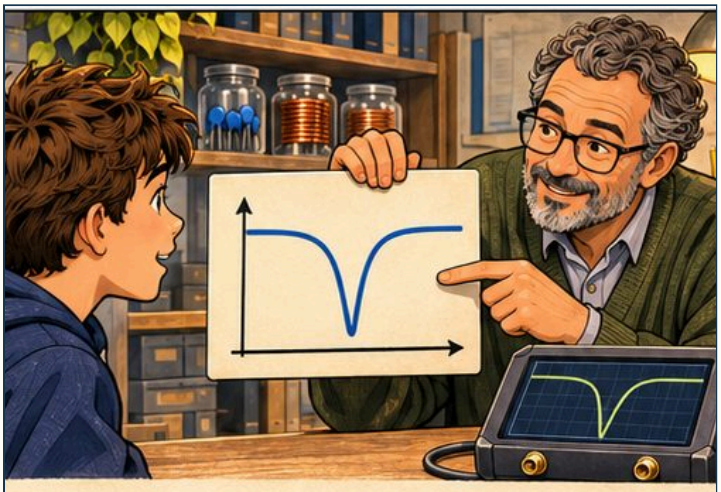
Other possible paths



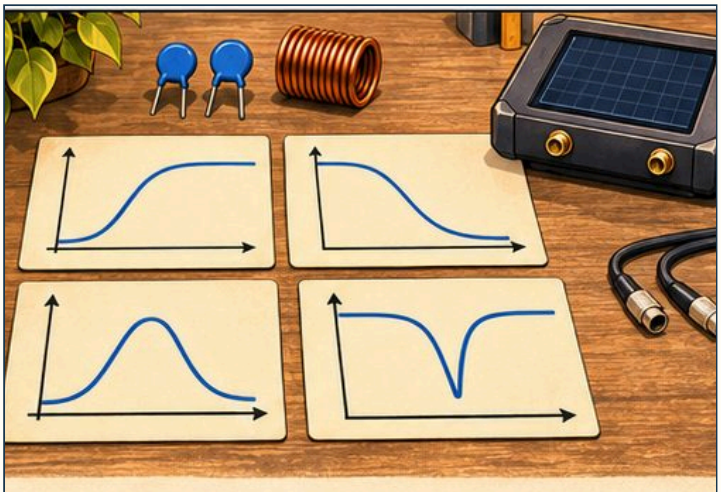
A high-pass filter attenuates low frequencies and passes high ones.



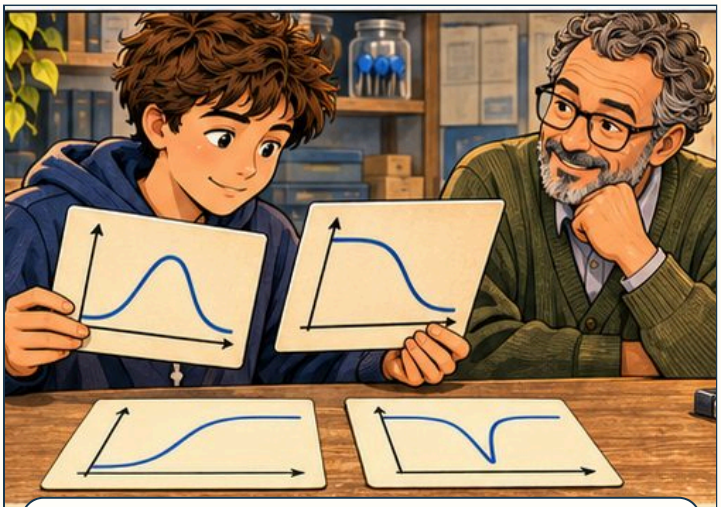
A band-pass filter favors a range between two limits.



A band-stop filter instead attenuates a selected range.



These families serve different needs.

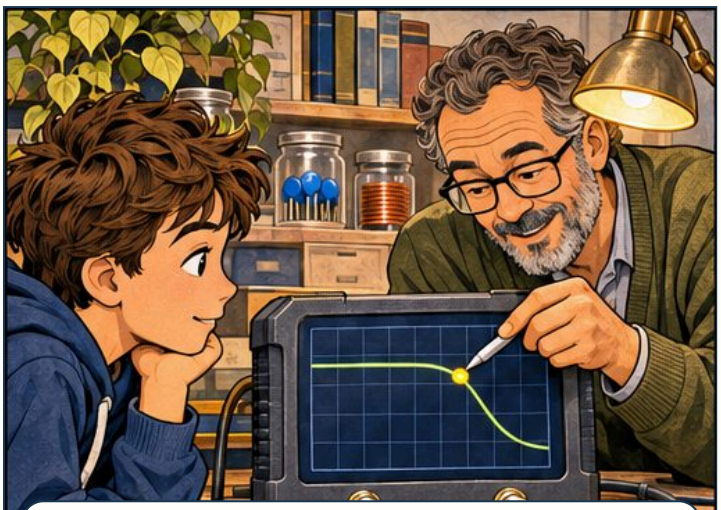


Their names describe a response, not universal quality.



The youngster puts three cards away for another workshop.

A cutoff that still passes signals



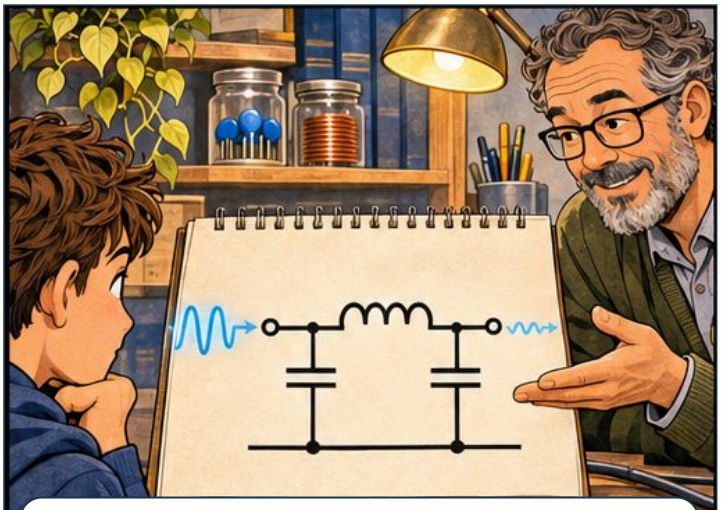
Here, cutoff frequency marks a reference level.



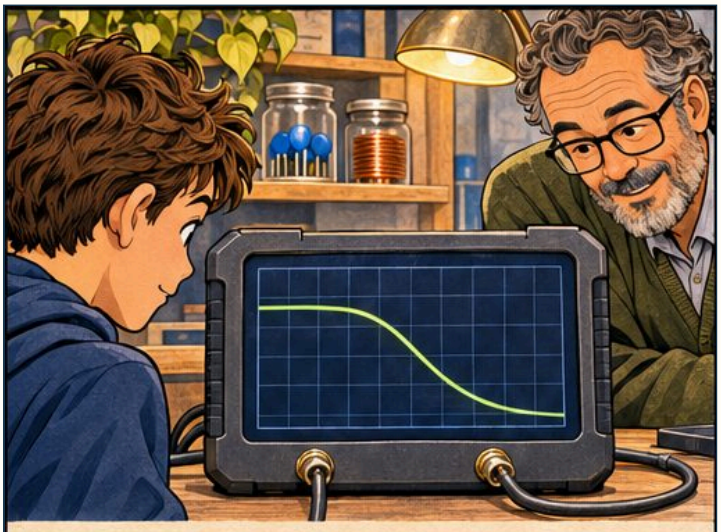
It does not mean the signal suddenly disappears.



For their ideal Butterworth, it corresponds to about −3 dB.



The filter therefore still passes energy at this frequency.



Beyond it, attenuation continues increasing.

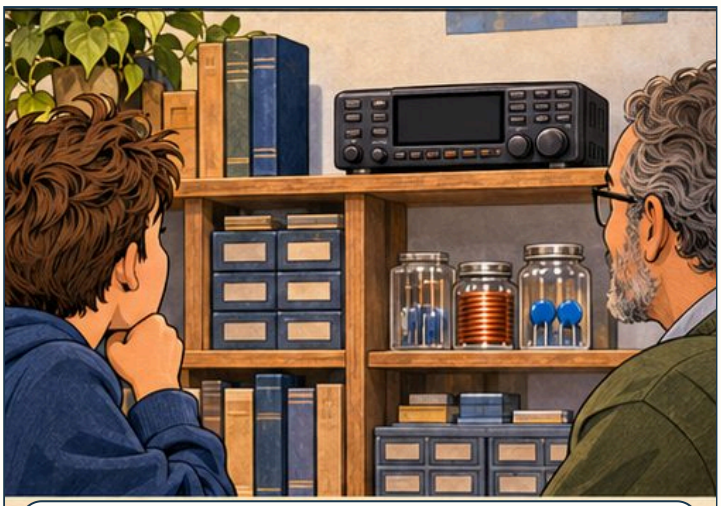


This clarification prevents an initial misconception.

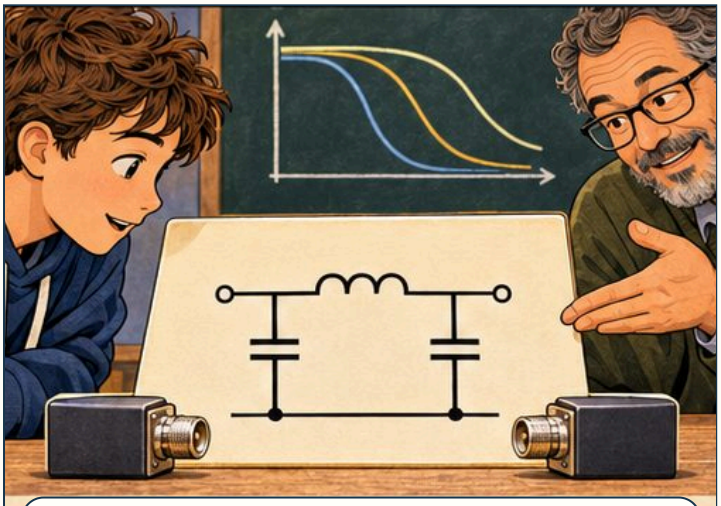
A laboratory example



They choose a theoretical cutoff of 10 MHz.



This learning example does not define a transmitting frequency.



The reference source and load will each be 50 Ω.



They will study the circuit on the bench, using a small signal.



No antenna or transmitter will be connected.

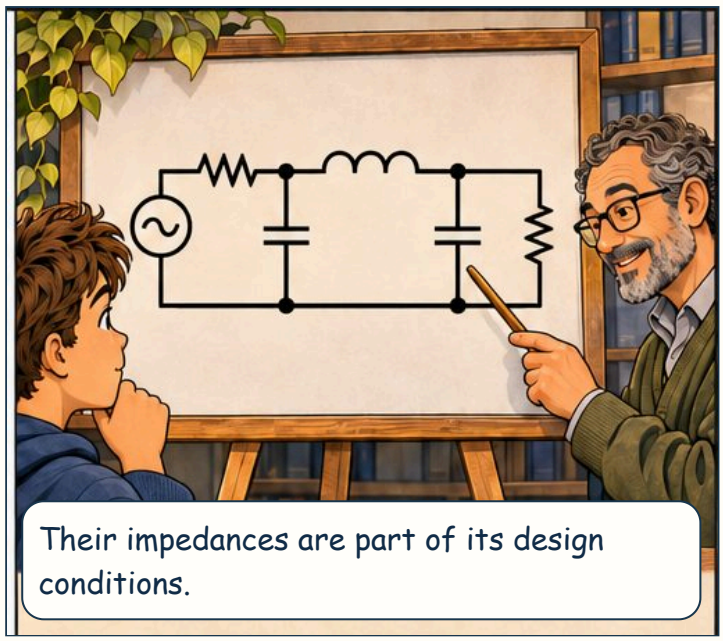


The goal is a measurable response, not a radio contact.

Why specify 50 ohms?



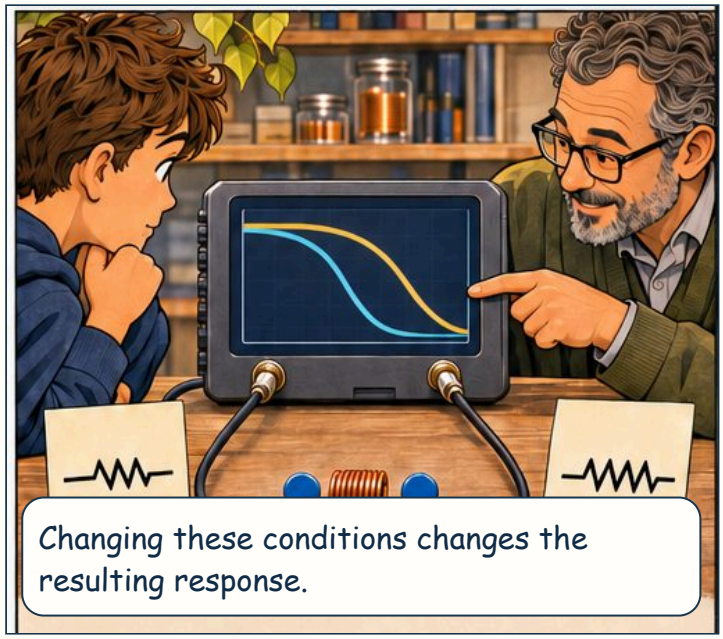
A filter operates between a source and a load.



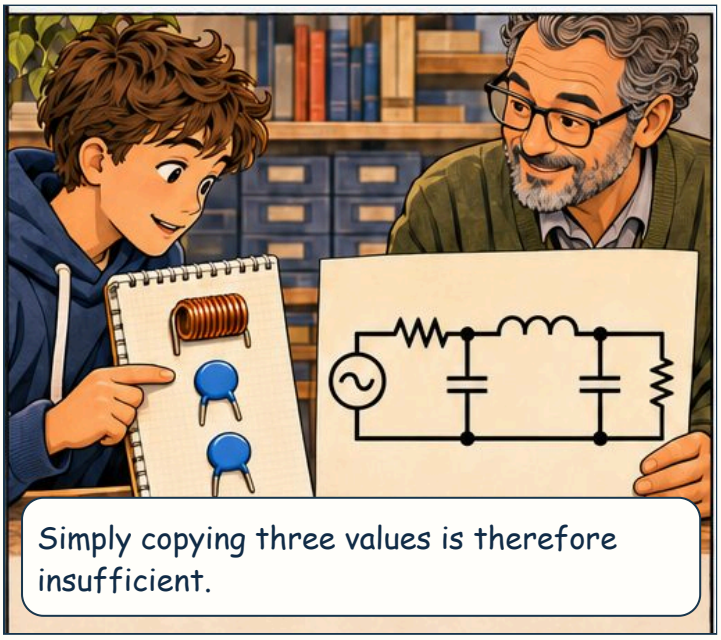
Their impedances are part of its design conditions.



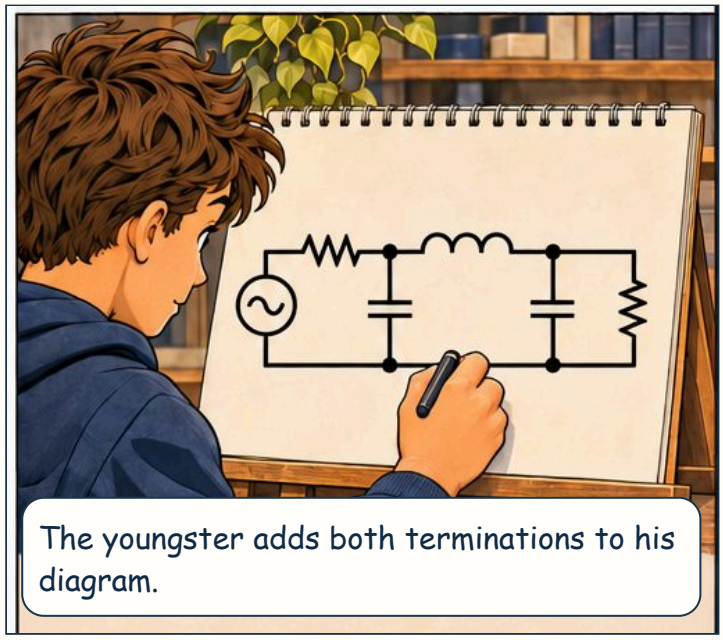
Here, each is ideally a resistive 50 Ω.



Changing these conditions changes the resulting response.

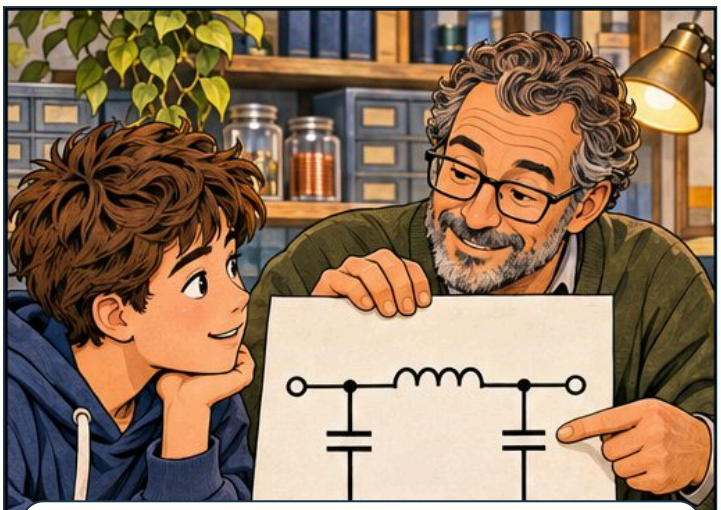


Simply copying three values is therefore insufficient.



The youngster adds both terminations to his diagram.

The model and the circuit



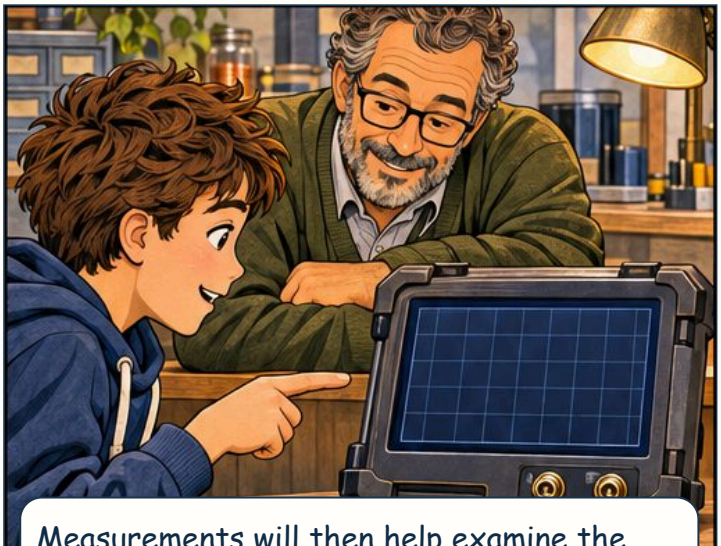
Calculations begin with ideal, lossless components.



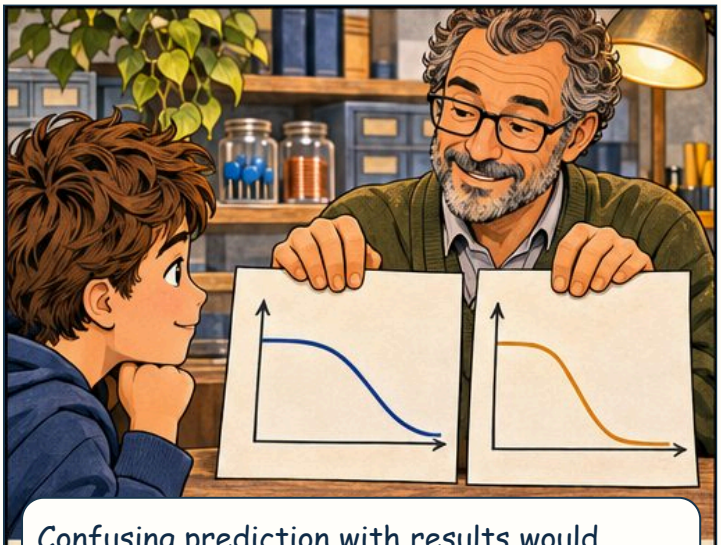
The real circuit will have resistances and parasitic effects.



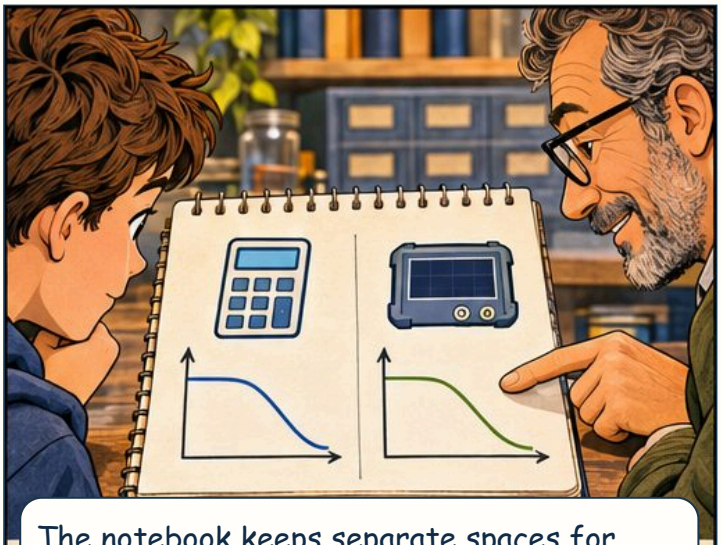
The model predicts an initial response.



Measurements will then help examine the differences.

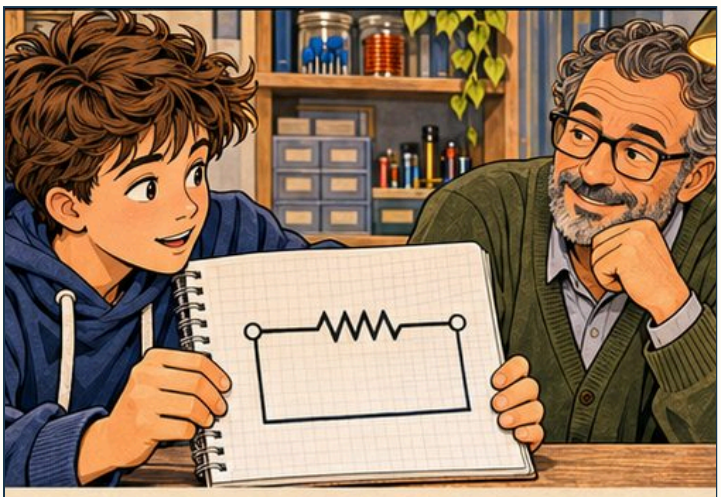


Confusing prediction with results would obscure those differences.

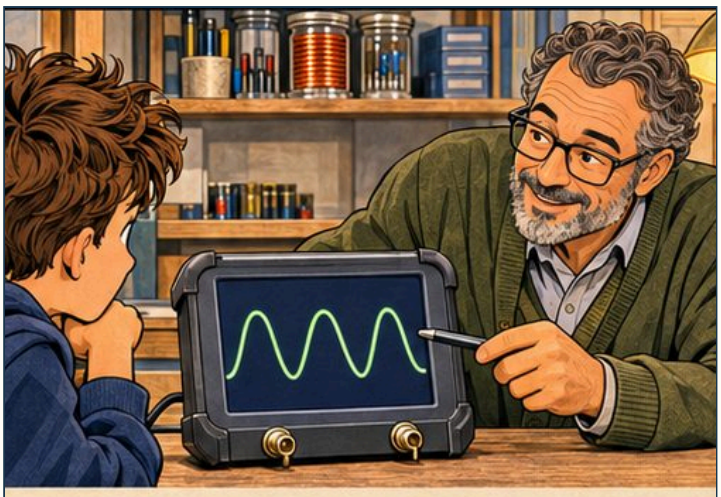


The notebook keeps separate spaces for each.

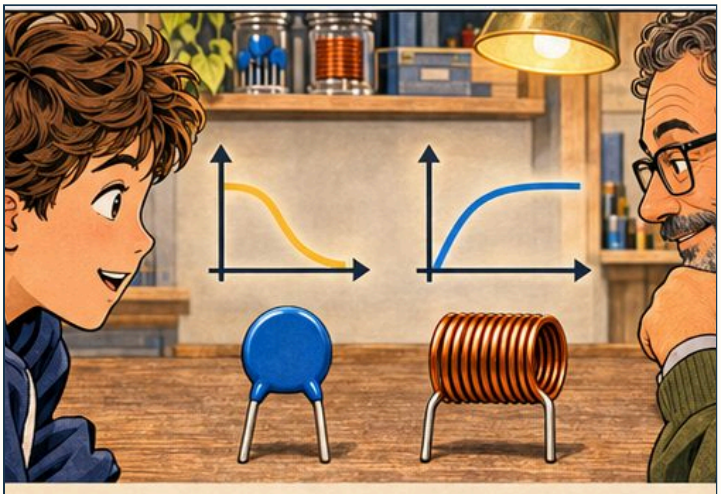
Resistance is no longer enough



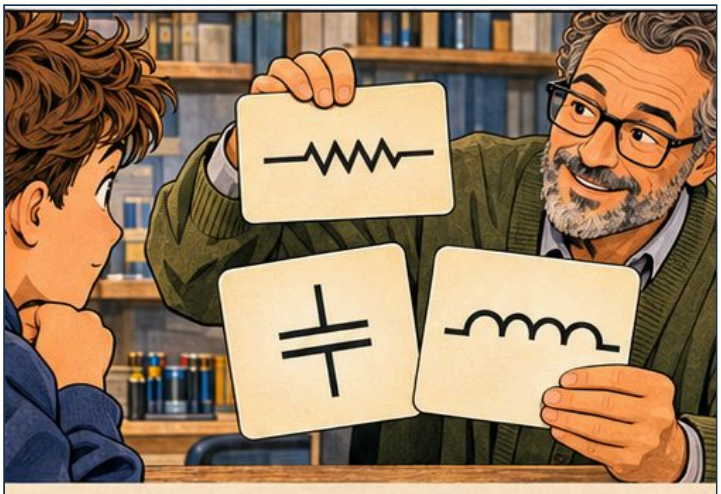
The previous volume linked voltage, current and resistance under DC.



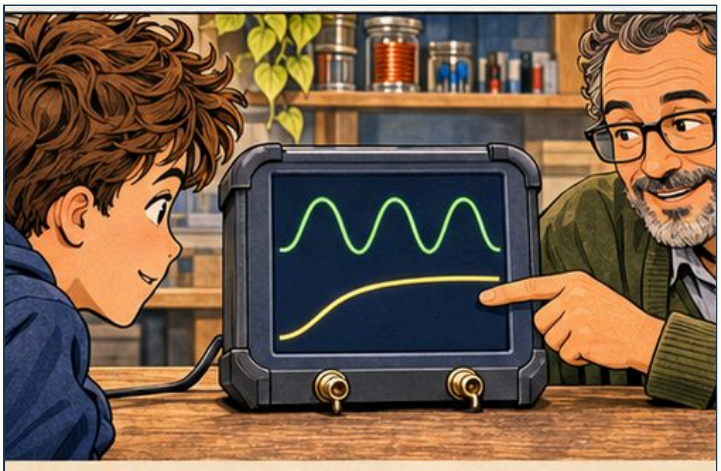
Here, the signal varies rapidly, and its frequency matters.



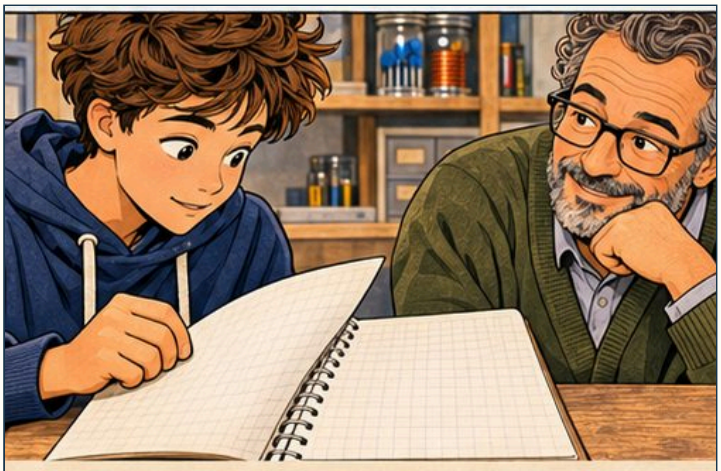
Capacitors and coils offer frequency-dependent opposition.



This reactance differs from simple resistance.



Impedance describes AC electrical behavior more broadly.

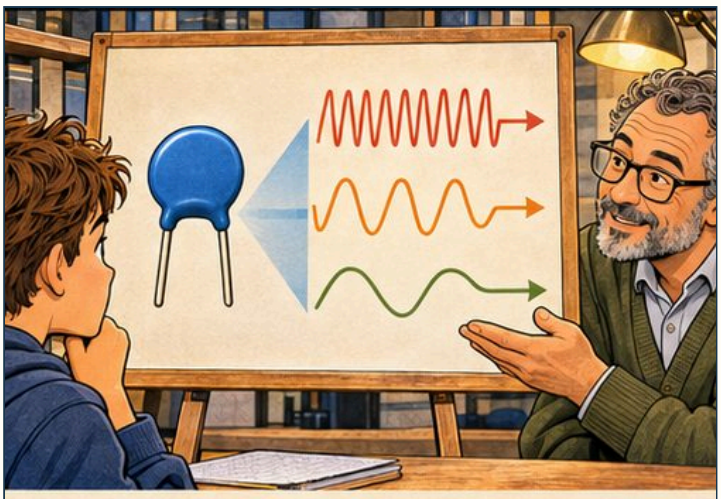


The youngster understands why a new model is needed.

The capacitor's role



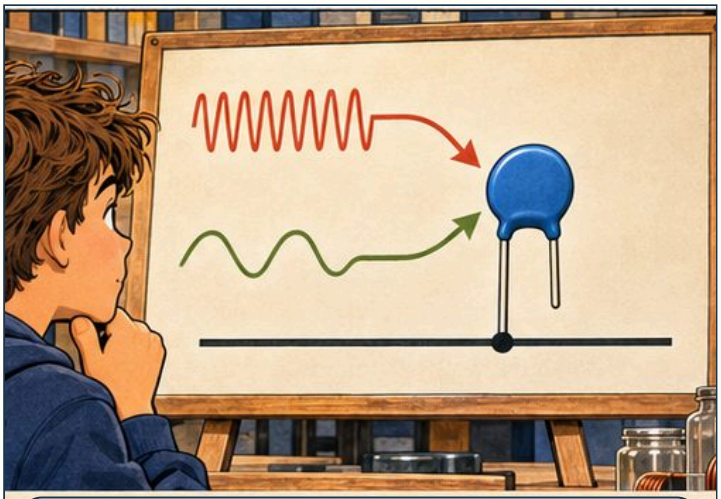
Capacitance is written C and measured in farads, F.



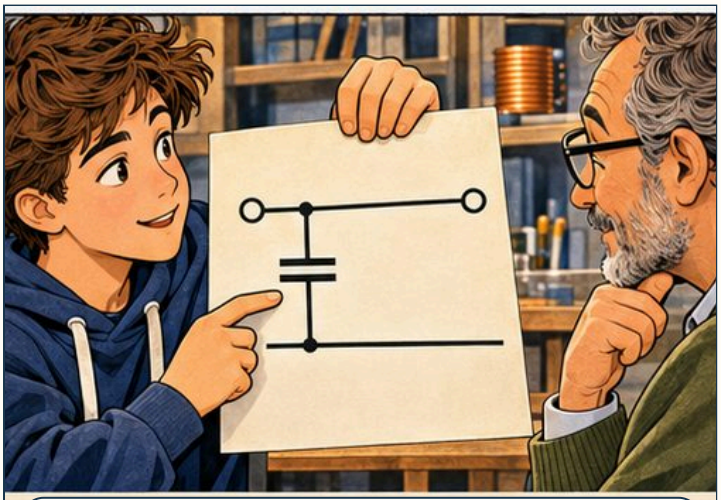
An ideal capacitor's reactance decreases as frequency increases.



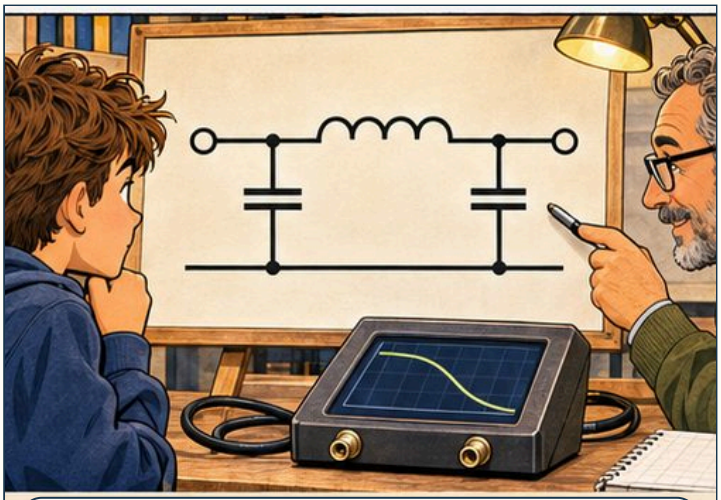
Its magnitude is $X_c = 1/(2\pi fC)$.



For fixed capacitance, high frequencies encounter less reactance.



In their filter, the capacitors will connect to circuit ground.

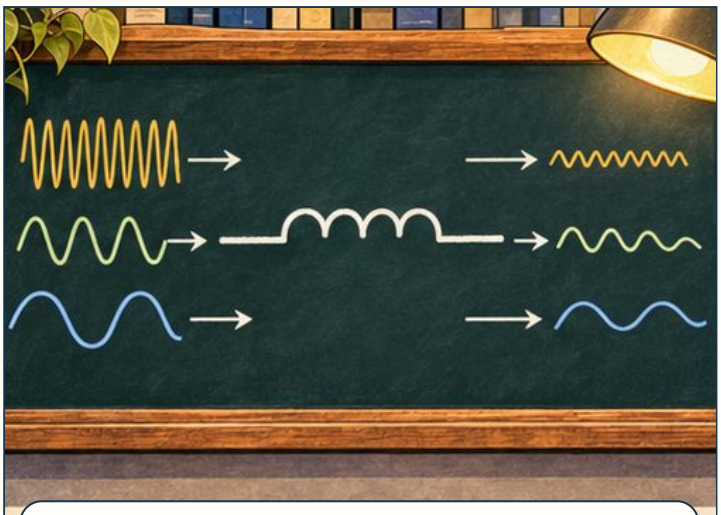


Their role also depends on the rest of the circuit.

The coil's role



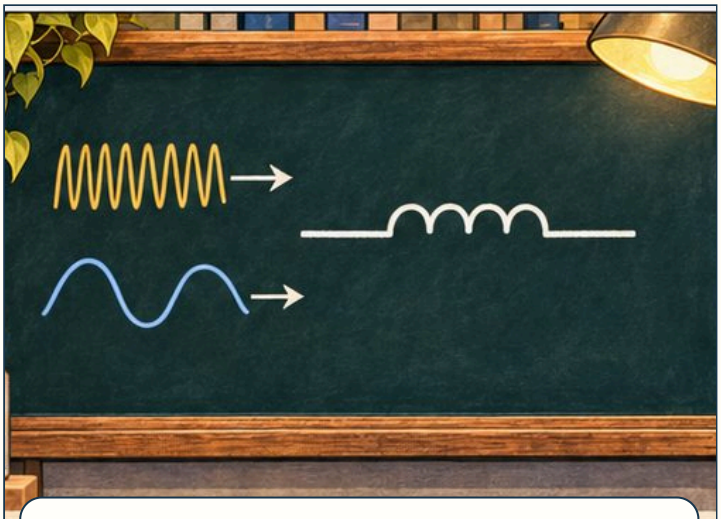
Inductance is written L and measured in henrys, H.



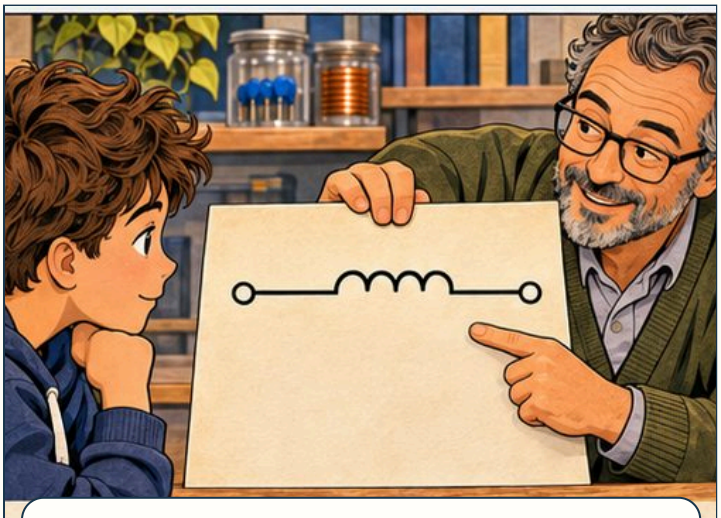
An ideal coil's reactance increases with frequency.



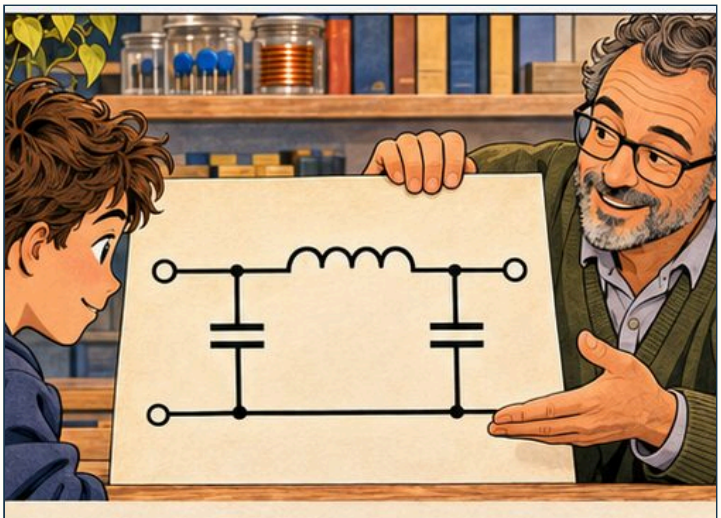
Its magnitude is XL = 2πfL.



For fixed inductance, high frequencies encounter greater reactance.

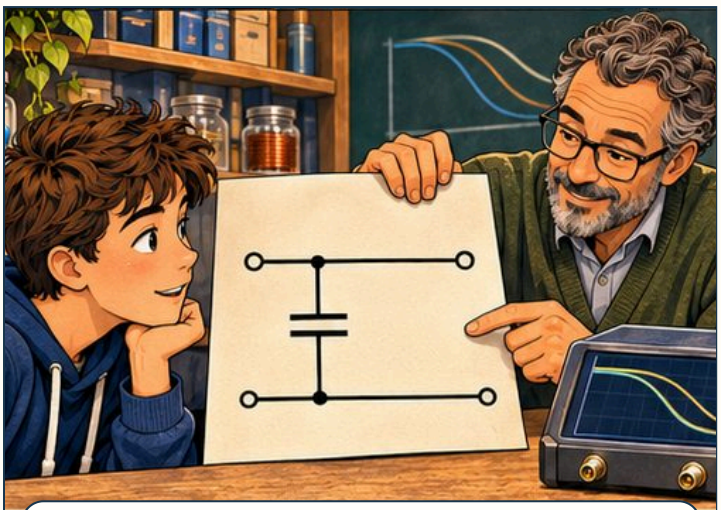


In their filter, the coil lies in the signal path.

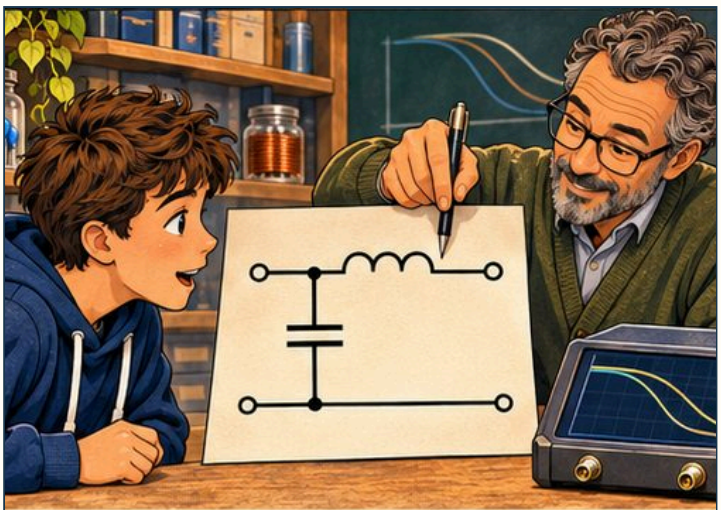


Both component types will act together.

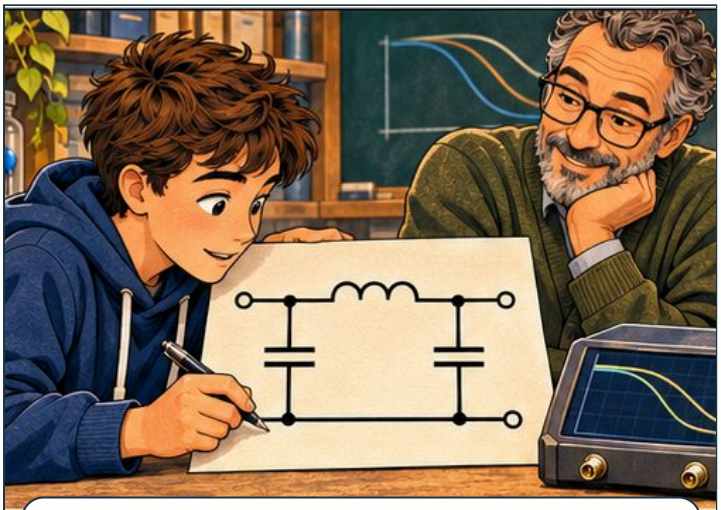
A circuit shaped like π



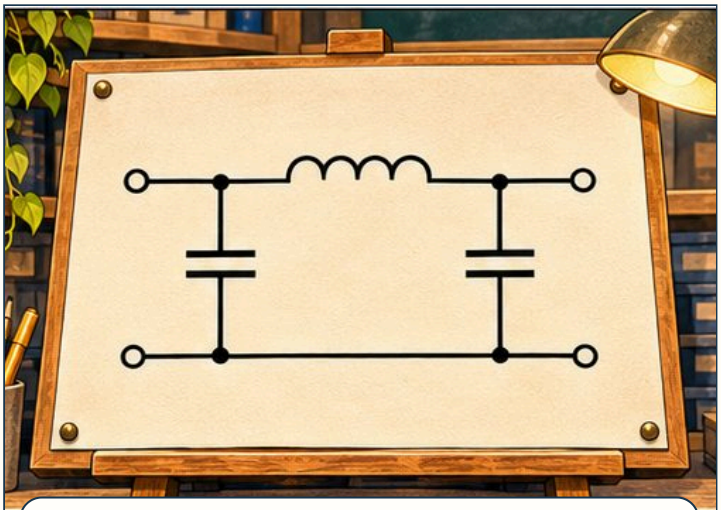
The input joins a first capacitor connected to circuit ground.



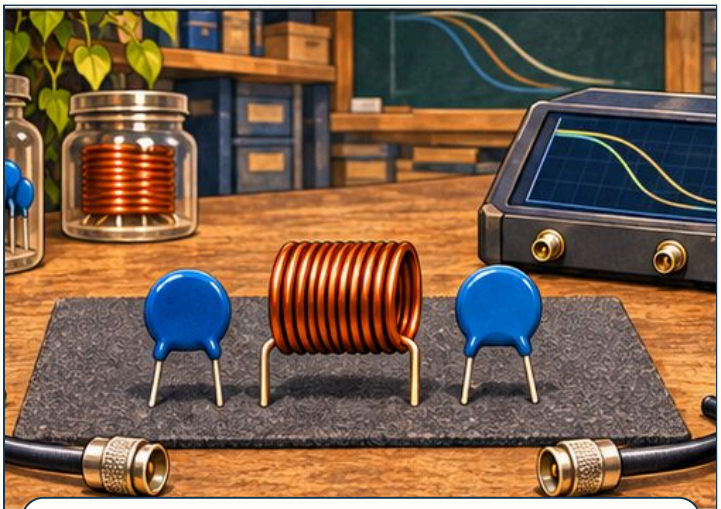
A series coil then connects input to output.



A second capacitor connects output to the same ground.



Two branches descend on either side of the coil.



This arrangement resembles the Greek letter π.

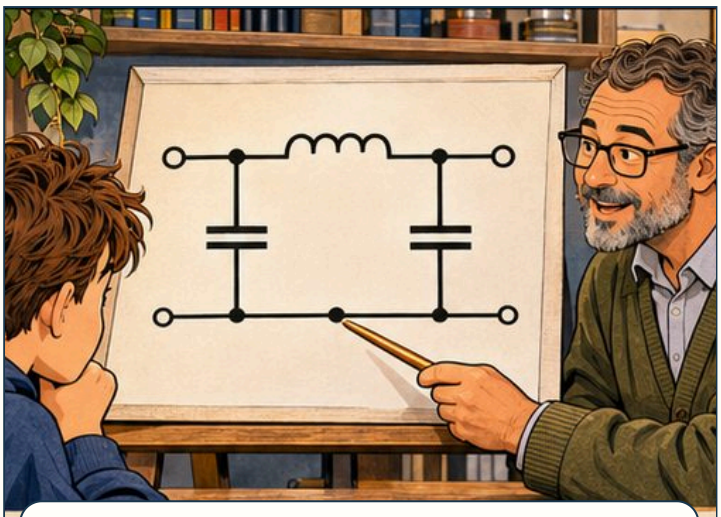


The youngster follows each connection with his pencil.

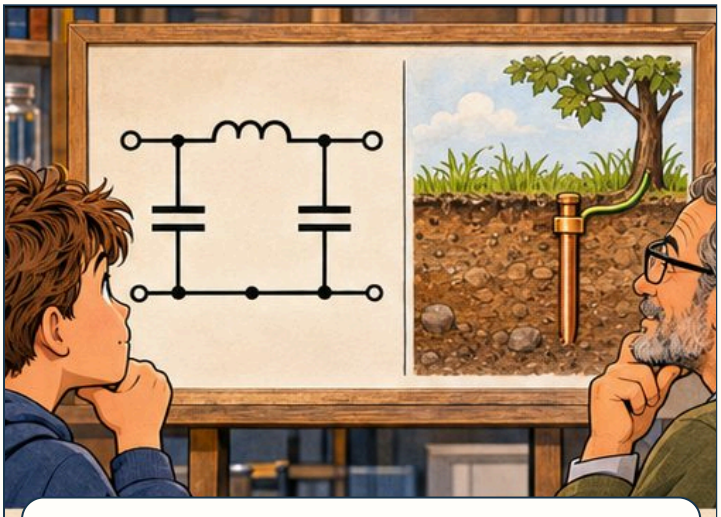
Ground in the diagram



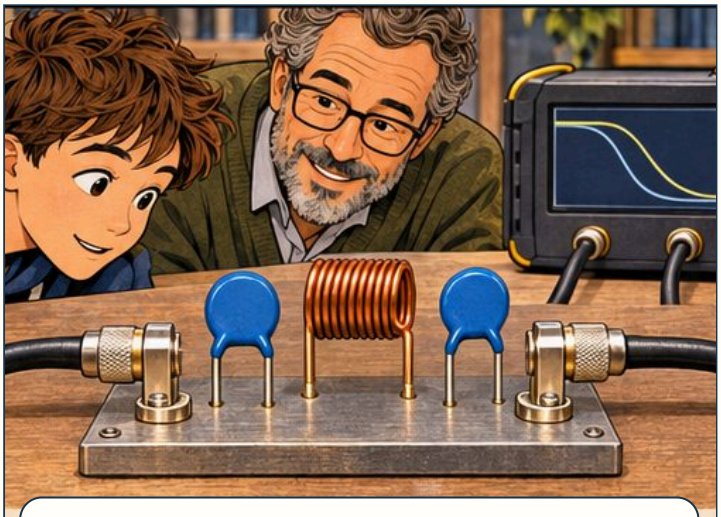
Both capacitors share a common electrical reference.



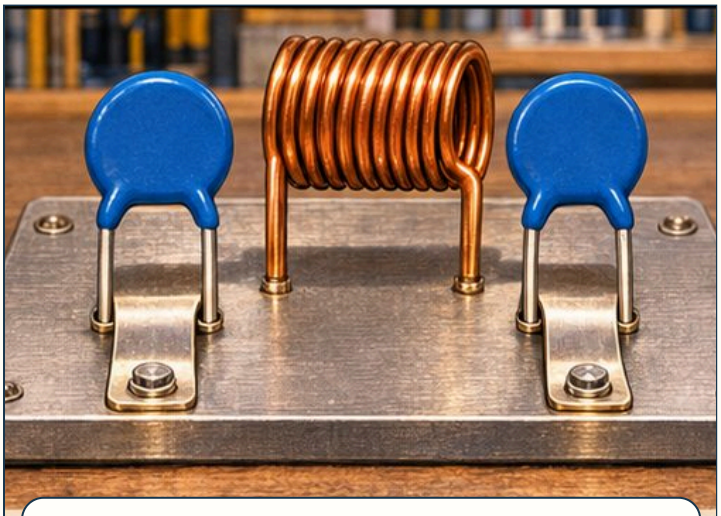
Here, the ground symbol represents that circuit reference.



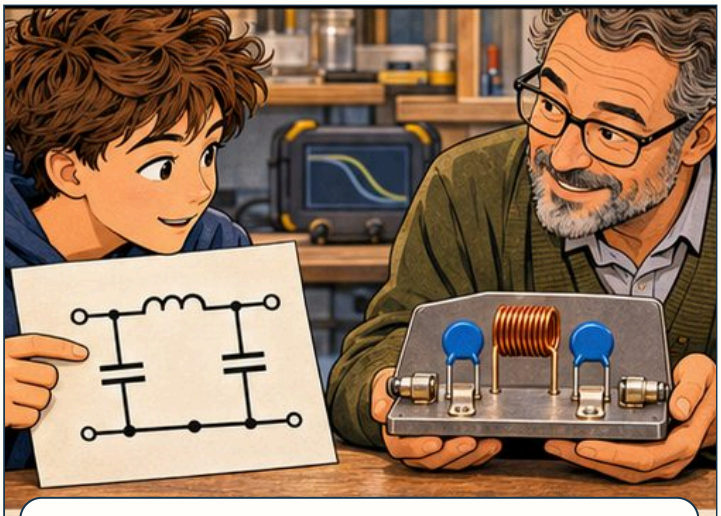
It does not automatically mean a connection to earth.



Coaxial shields join this ground as the design requires.



A short connection limits certain parasitic effects.

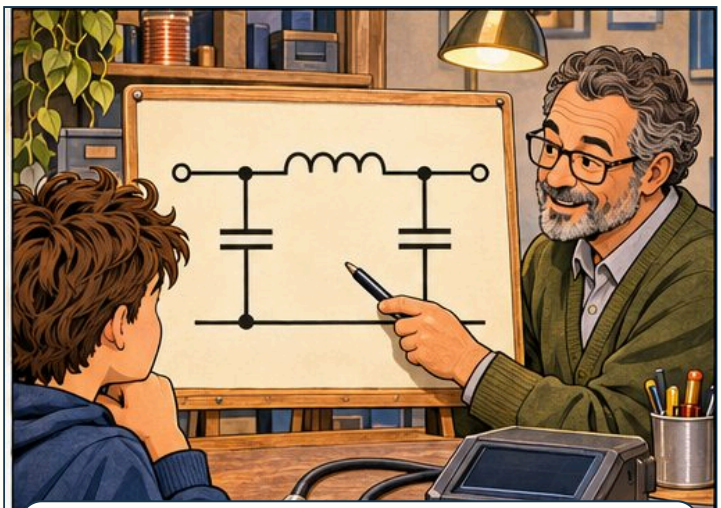


The youngster distinguishes the symbol from its physical implementation.

Three elements, one order



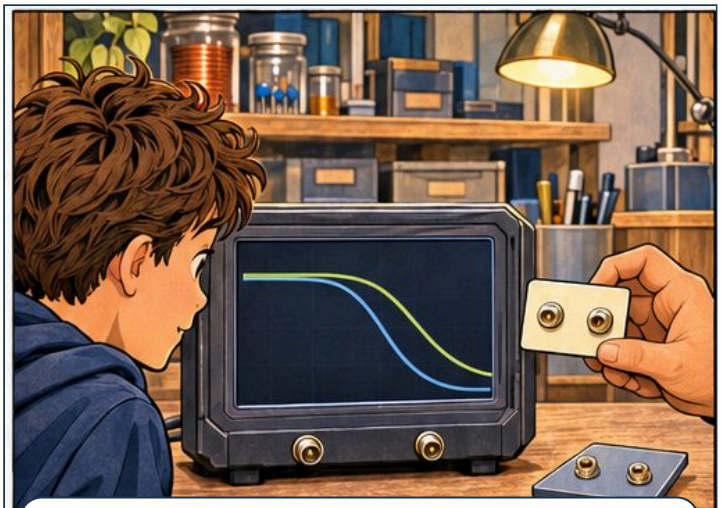
This ideal network has three reactive elements: C, L and C.



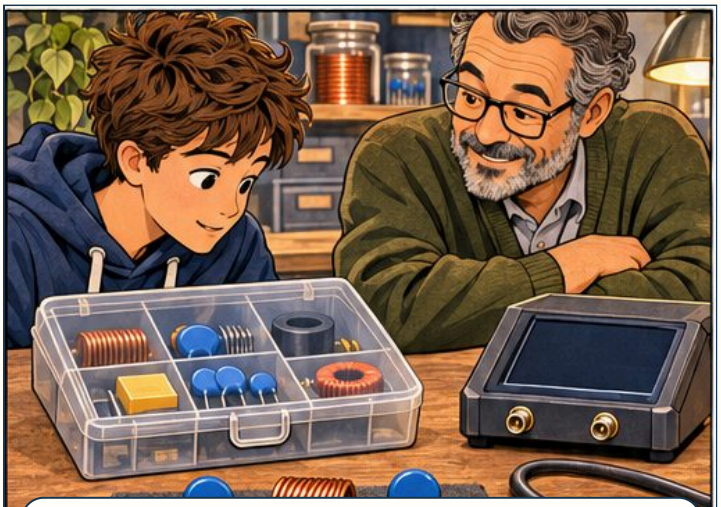
Here, they form a third-order low-pass filter.



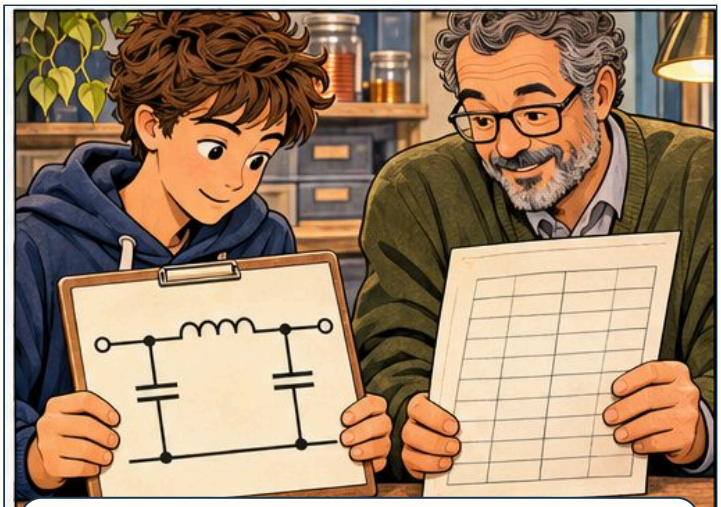
The order characterizes, among other things, the model's eventual slope.



An unsuitable impedance would nevertheless change the response.



Adding components randomly cannot create the desired filter.

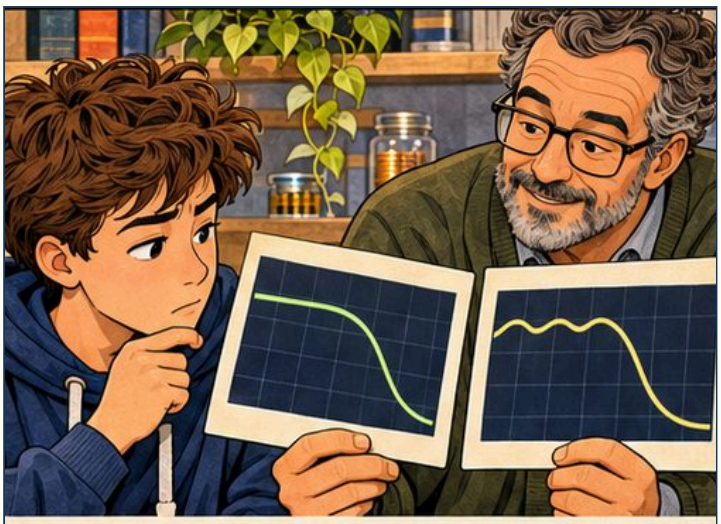


The circuit topology must accompany its calculations.

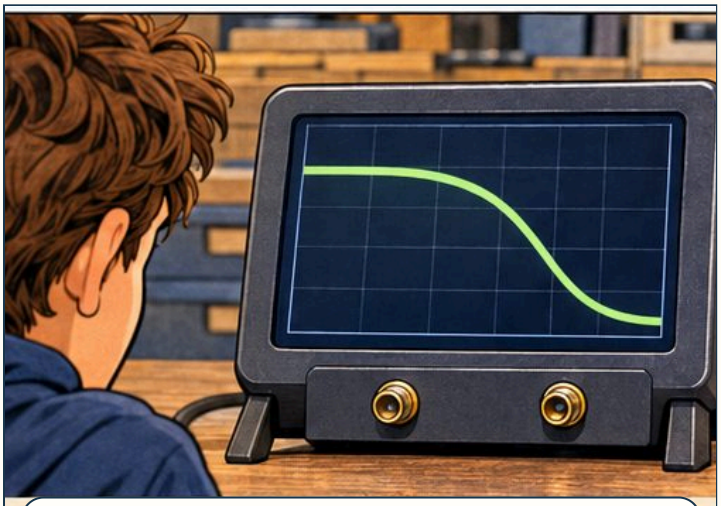
Why Butterworth?



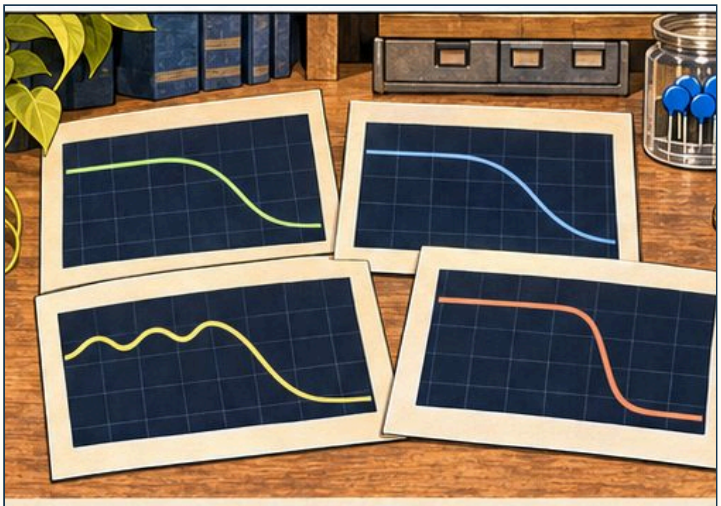
A Butterworth response is maximally flat in the passband.



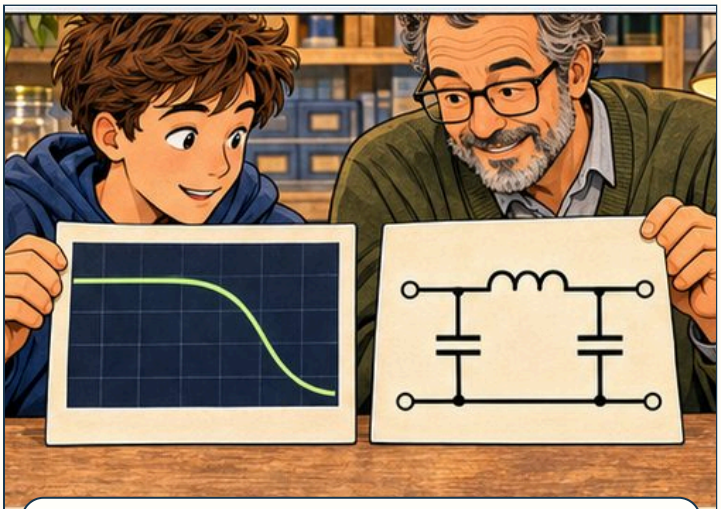
Its ideal model has no ripple in that band.



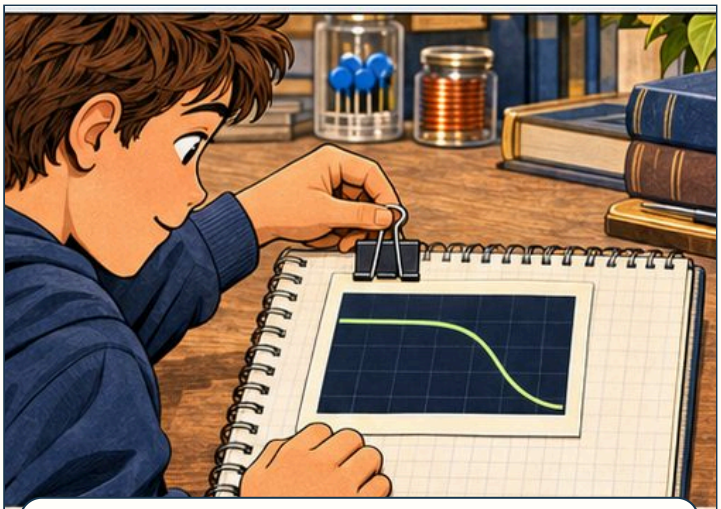
The transition remains gradual, with a characteristic curvature.



Other responses make different trade-offs.

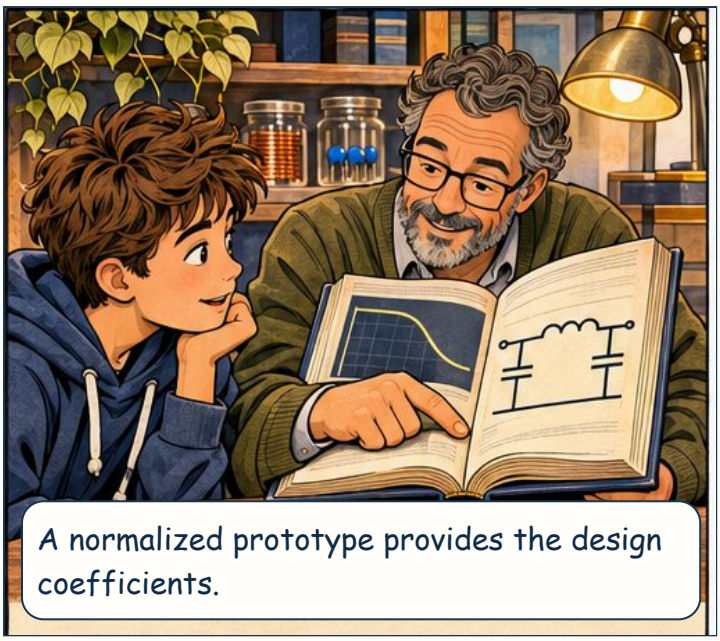


They choose this family for a clear first design.

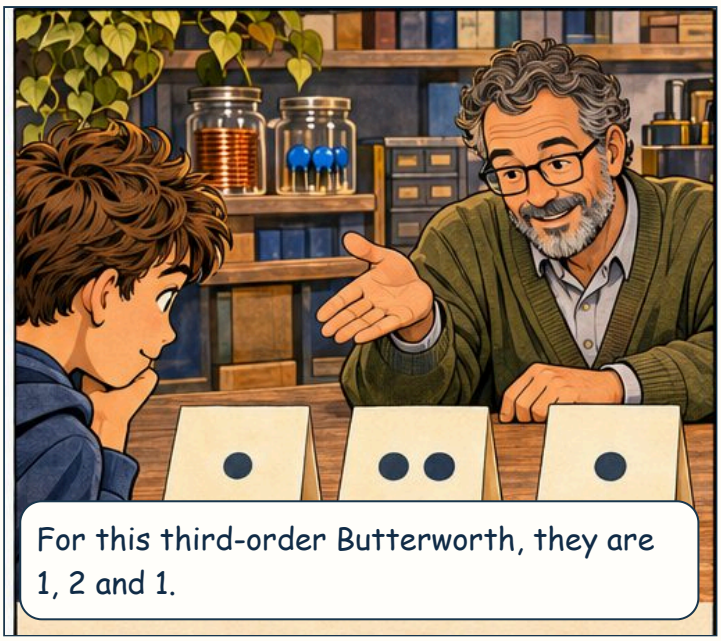


The name therefore specifies more than simply “low-pass”.

Starting with a prototype



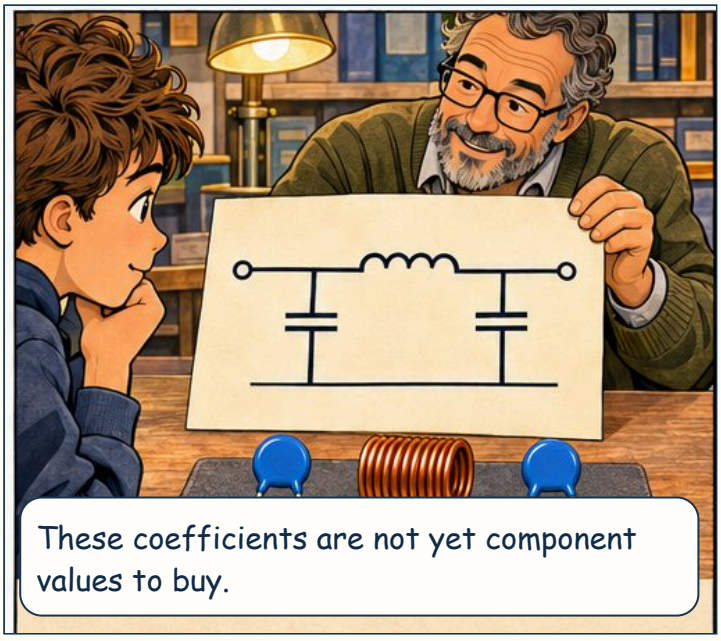
A normalized prototype provides the design coefficients.



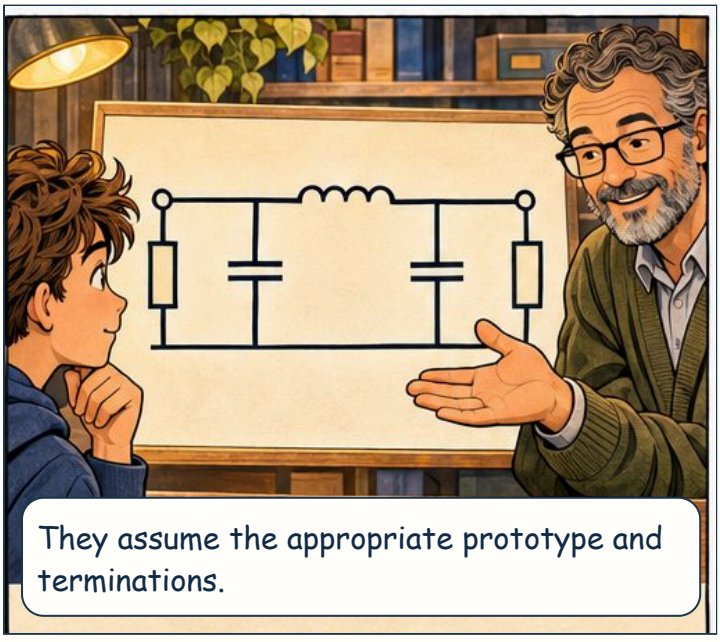
For this third-order Butterworth, they are 1, 2 and 1.



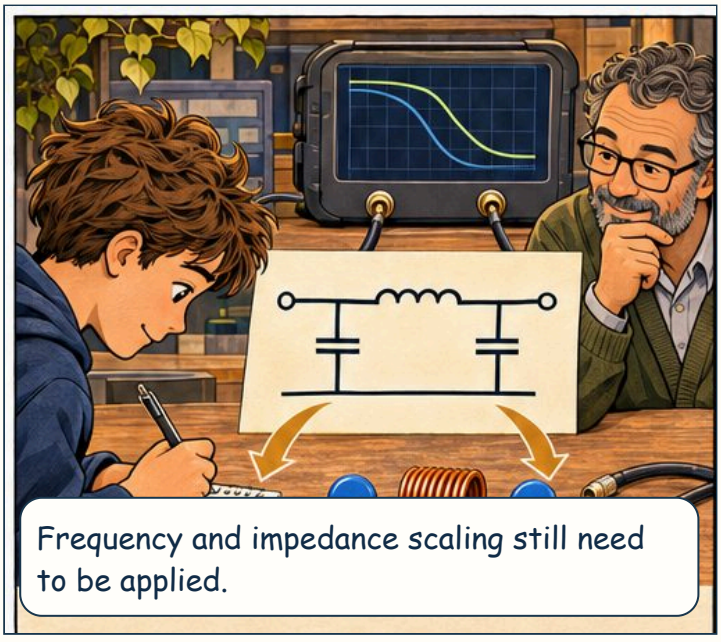
They correspond, in order, to capacitor, coil, capacitor.



These coefficients are not yet component values to buy.

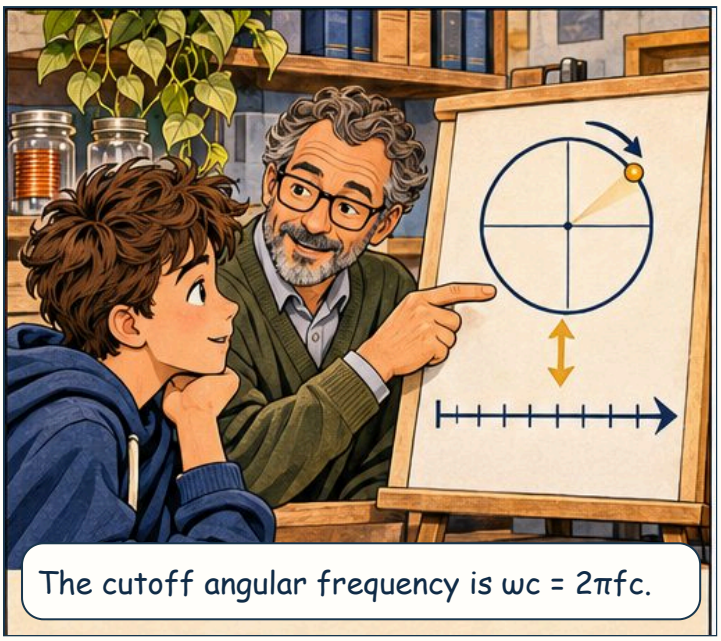


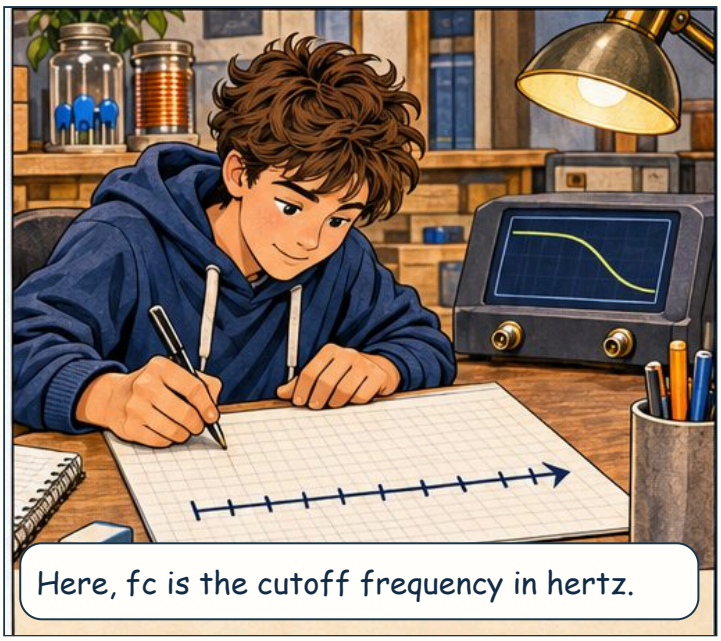
They assume the appropriate prototype and terminations.

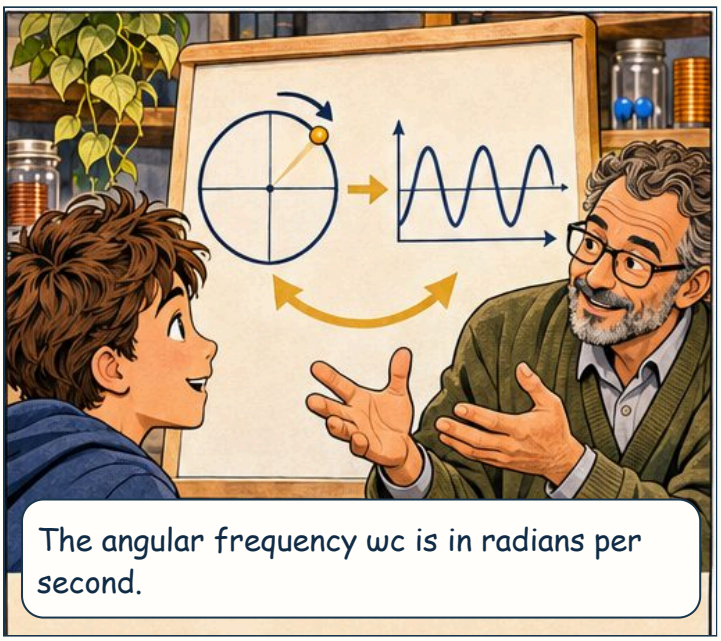


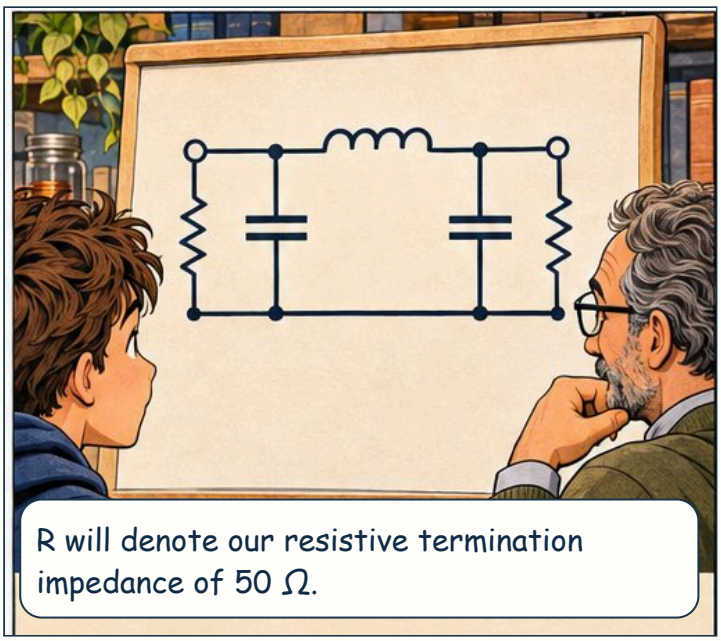
Frequency and impedance scaling still need to be applied.

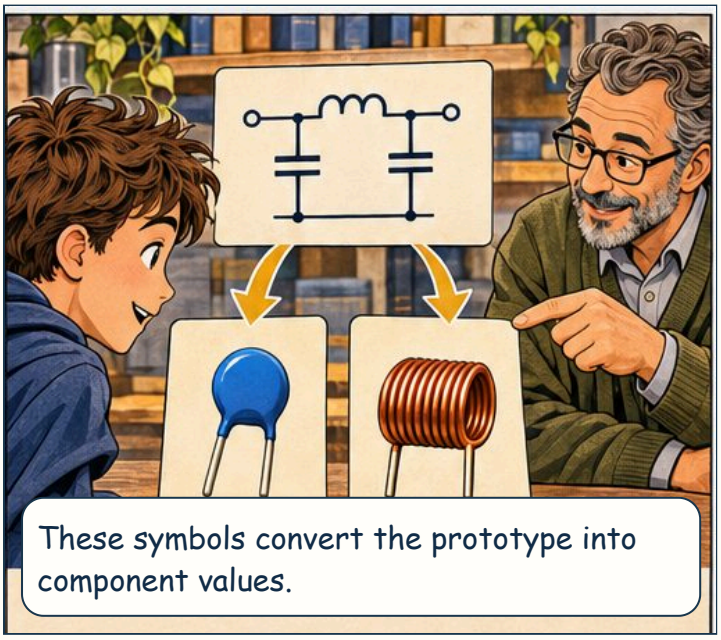
Changing scale

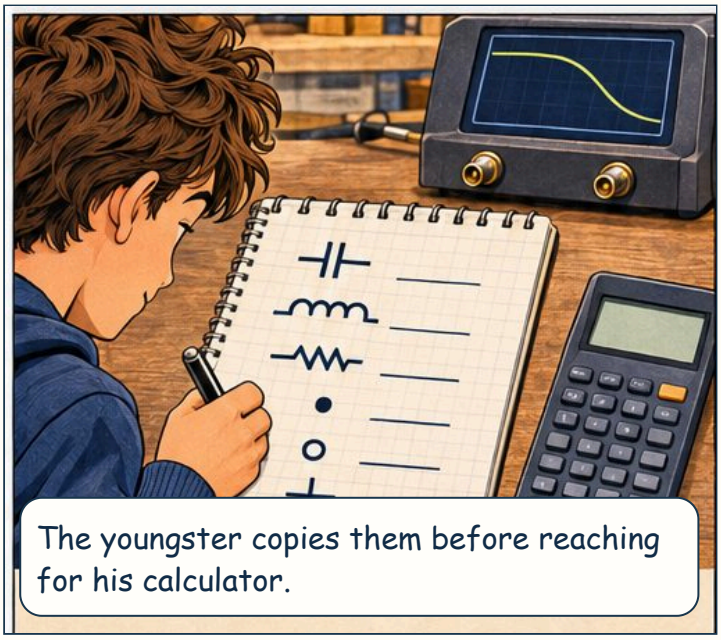








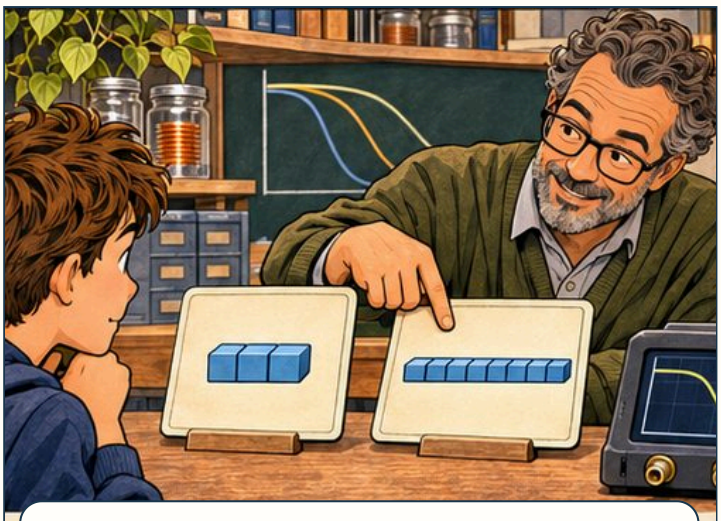




Units before numbers



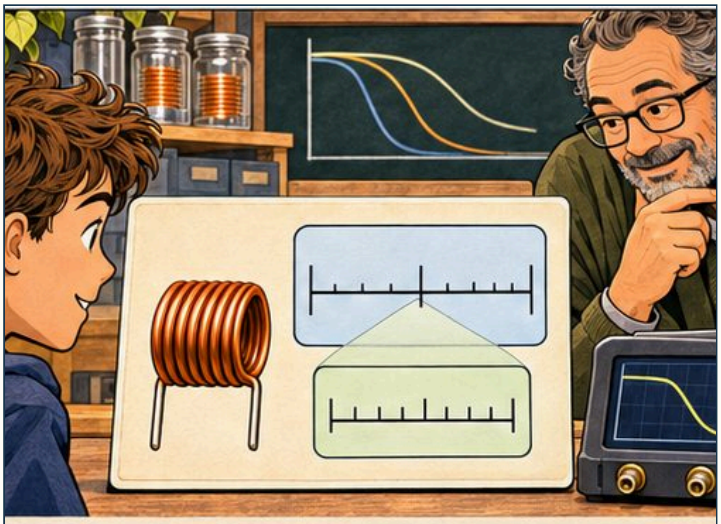
One megahertz equals one million hertz.



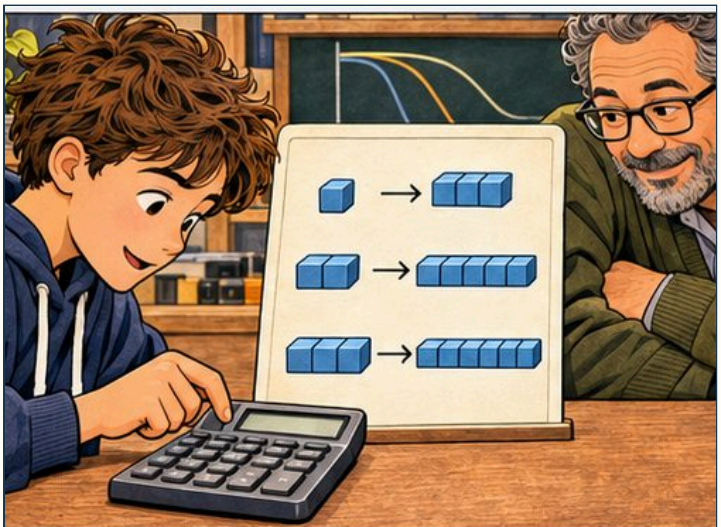
Their 10 MHz cutoff therefore equals 10 000 000 Hz.



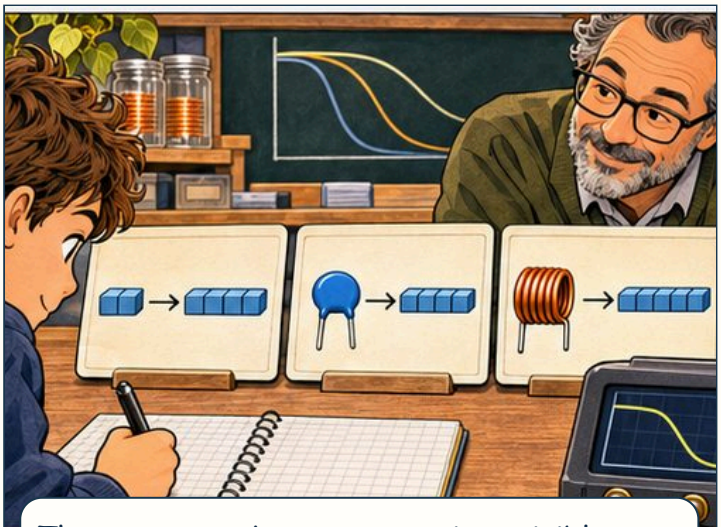
One picofarad equals 10^{-12} F.



One microhenry equals 10^{-6} H.

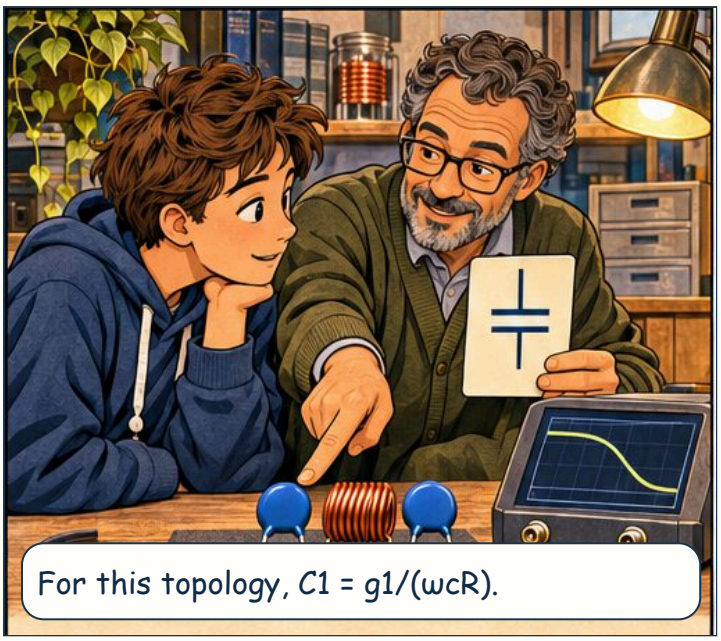


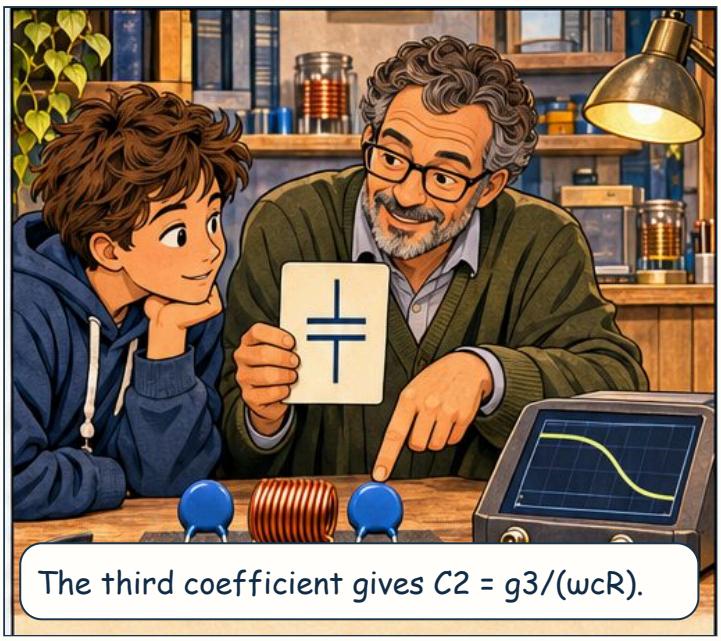
The formulas will first use base units.

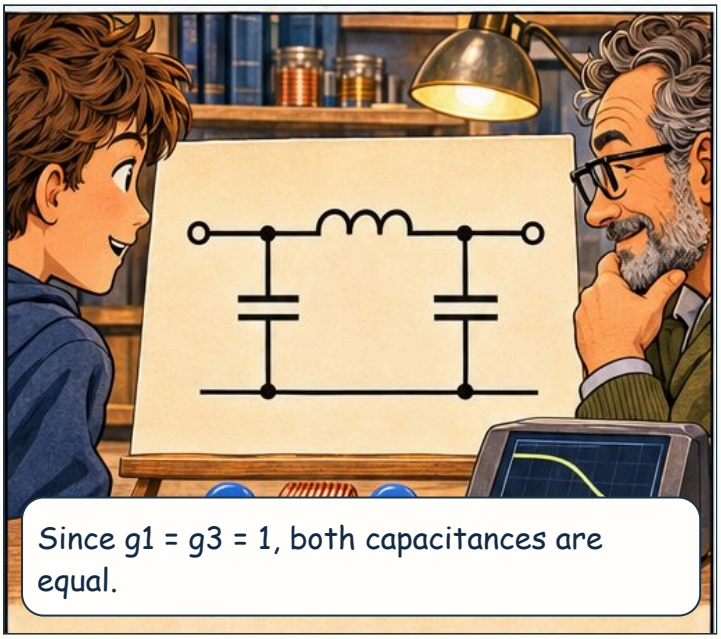


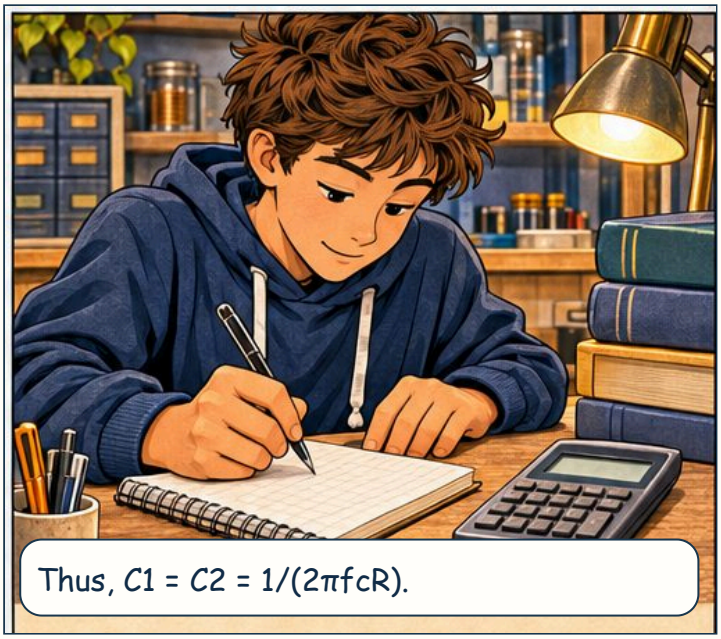
The youngster keeps conversions visible beside his calculations.

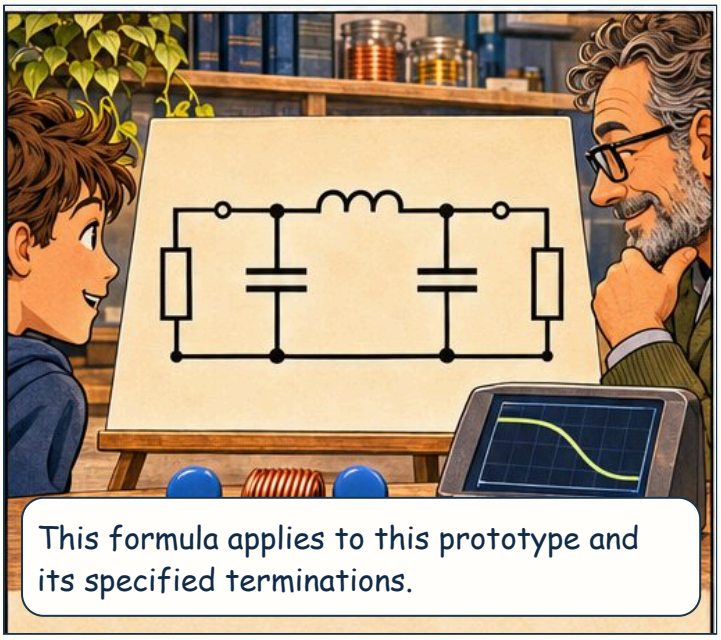
The capacitor formulas

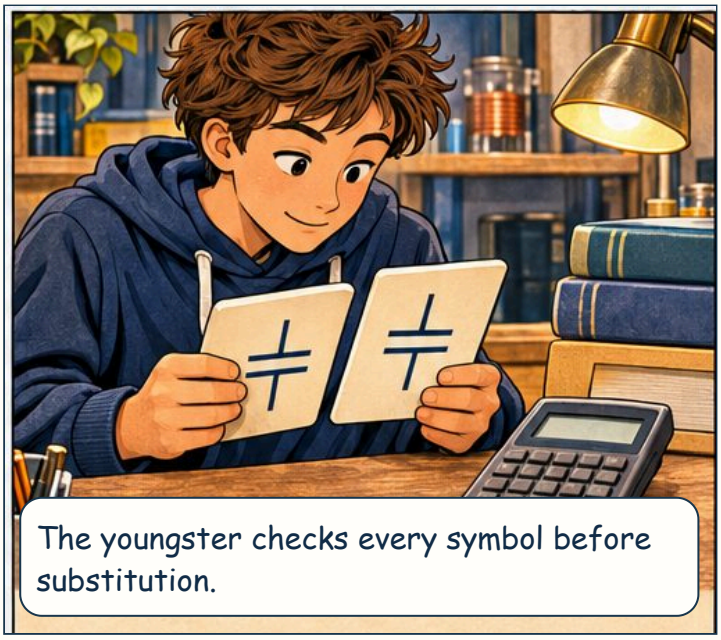




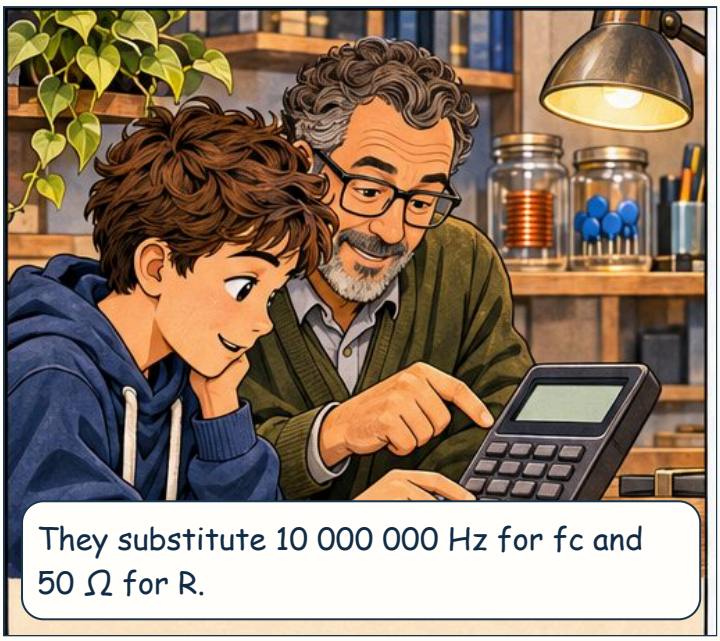




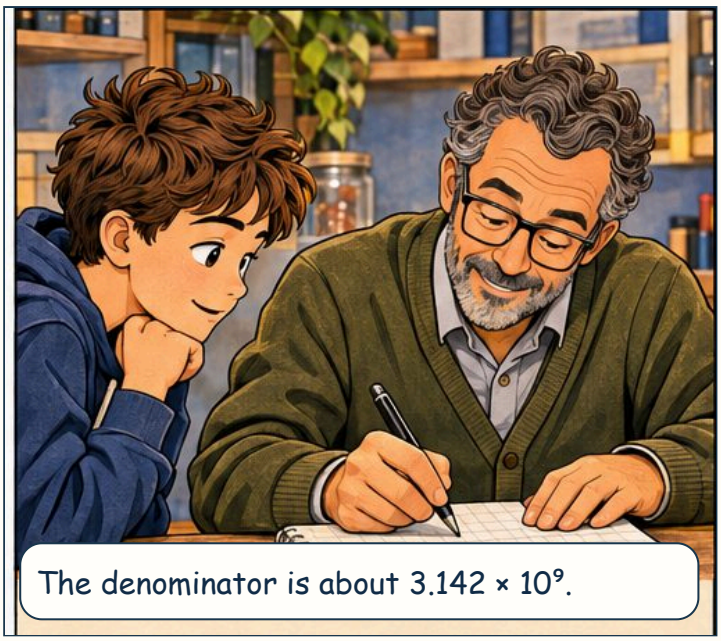




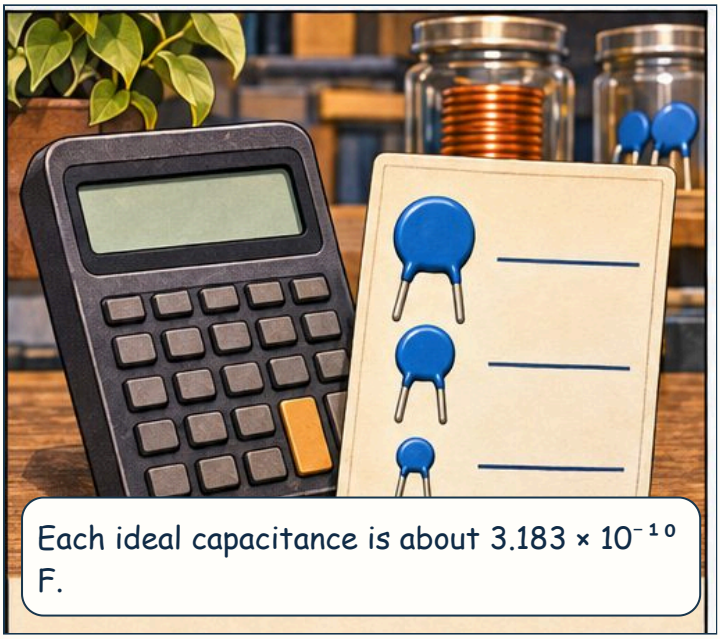
Calculating capacitances



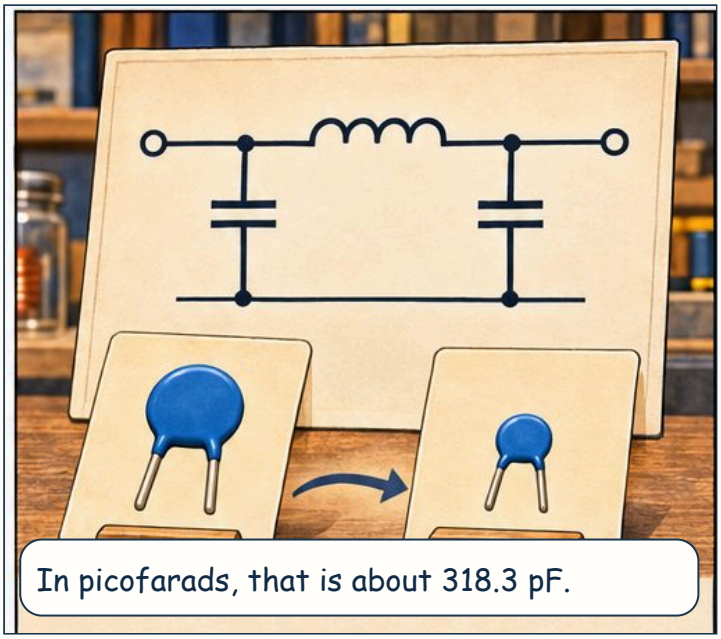
They substitute 10 000 000 Hz for fc and 50 Ω for R.



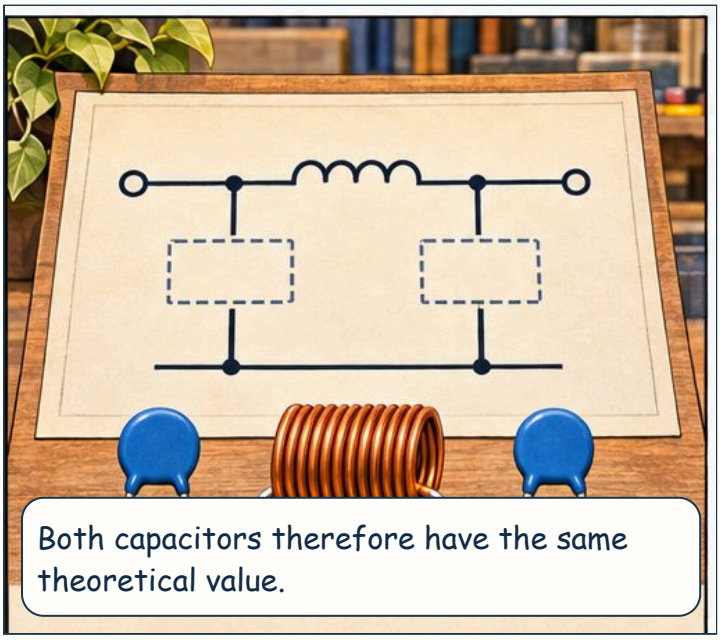
The denominator is about 3.142 × 10^{9}.



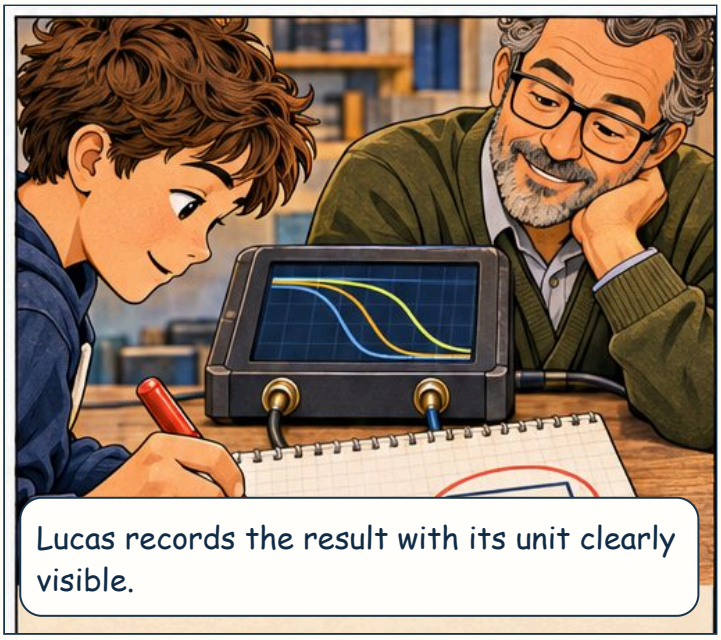
Each ideal capacitance is about 3.183 × 10^{-10} F.



In picofarads, that is about 318.3 pF.

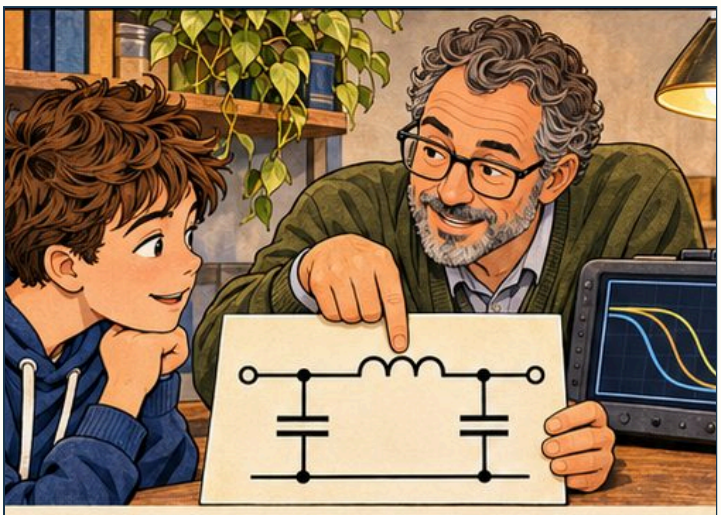


Both capacitors therefore have the same theoretical value.



Lucas records the result with its unit clearly visible.

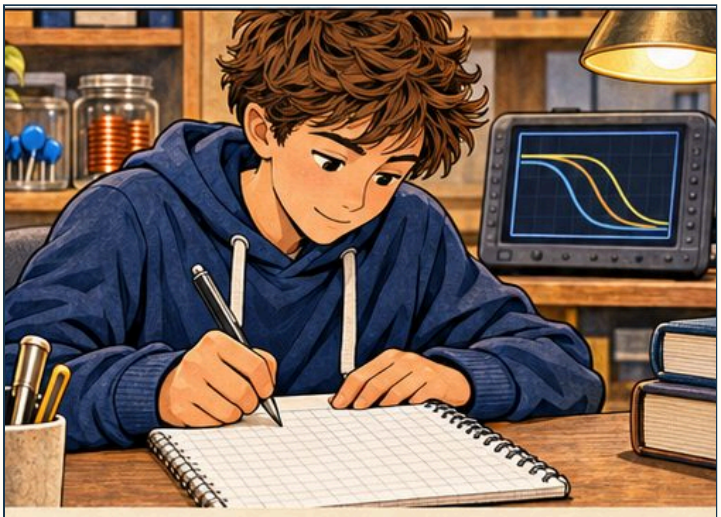
The coil formula



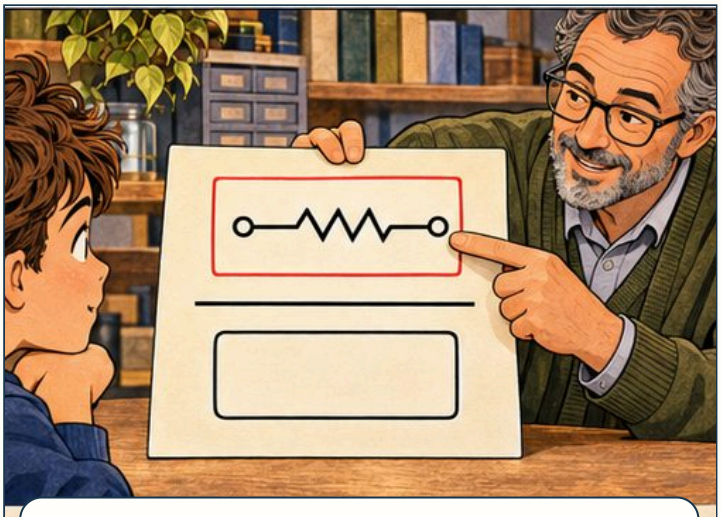
For the series coil, L = g2R/ωc.



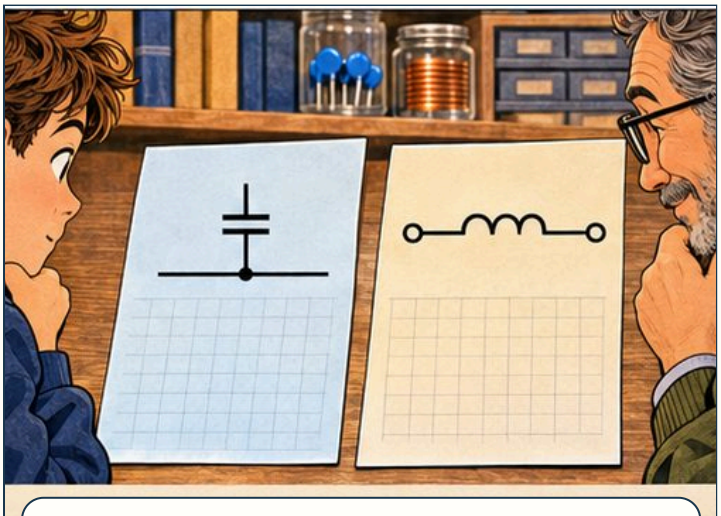
Here, the middle coefficient is g2 = 2.



Thus, L = 2R/(2πfc).



This time, termination resistance appears in the numerator.

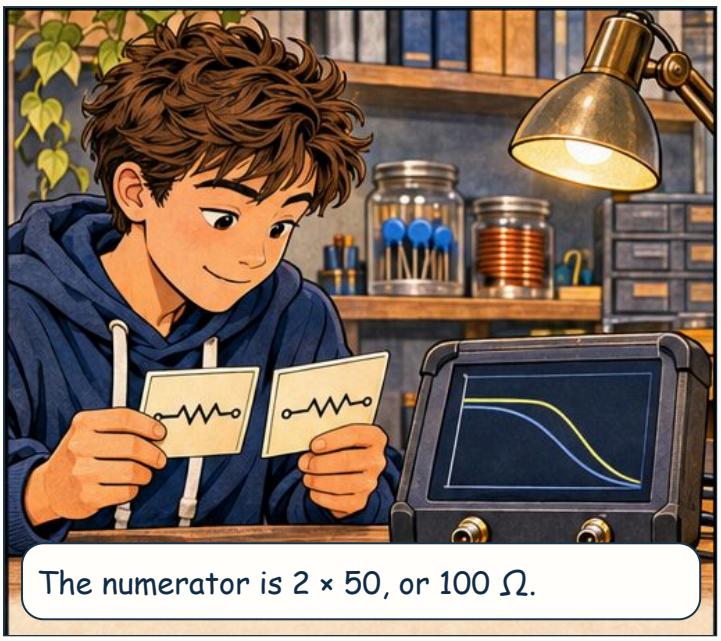


The youngster compares this formula with the capacitor formula.

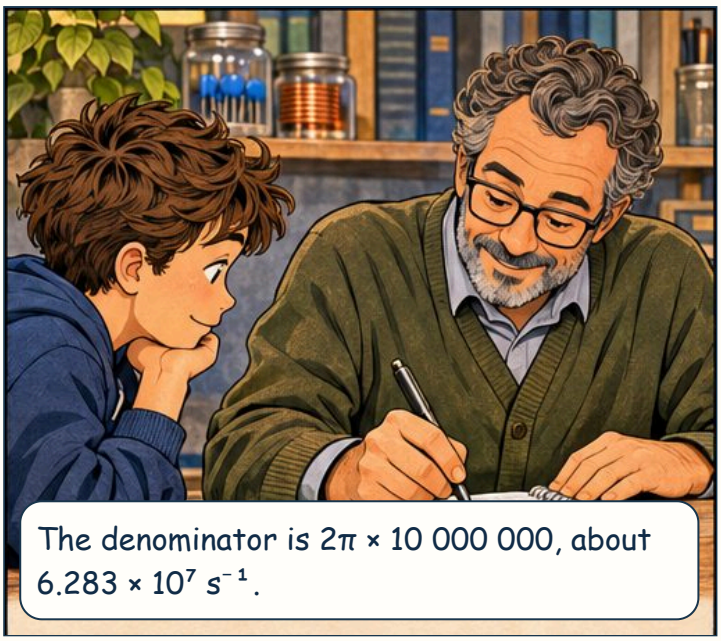


A visual resemblance is no substitute for checking.

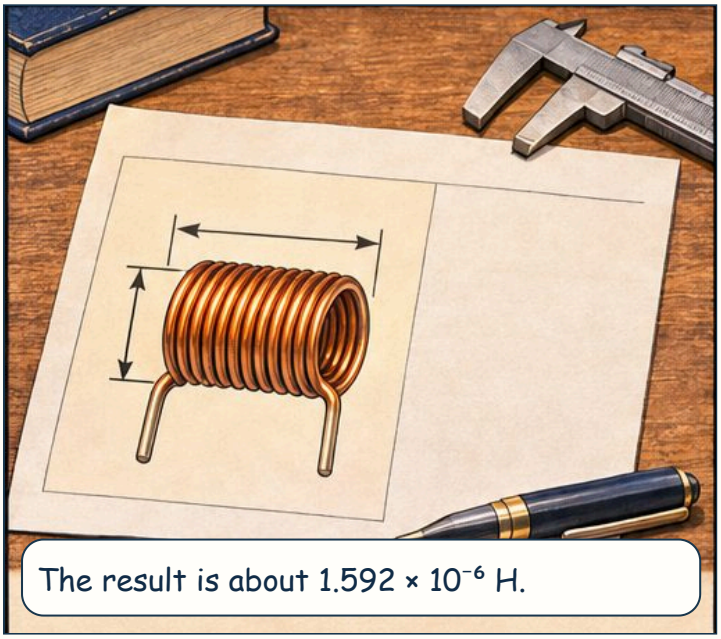
Calculating inductance



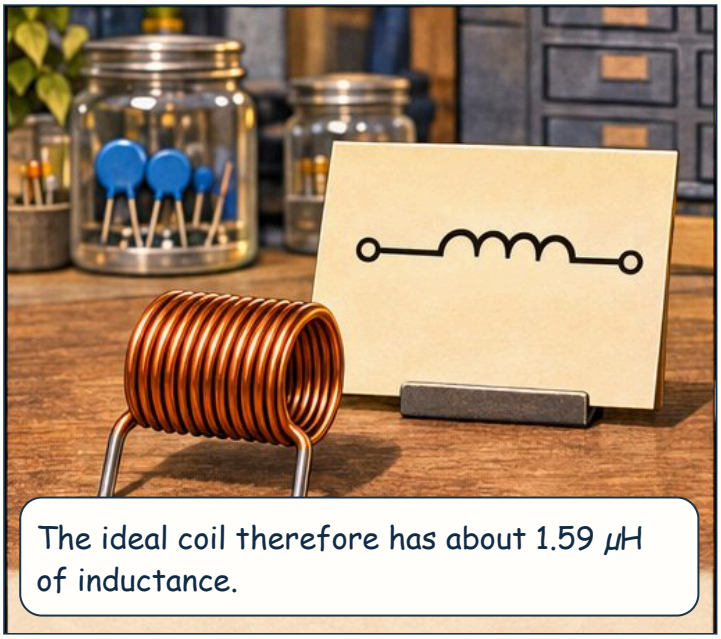
The numerator is 2 × 50, or 100 Ω.



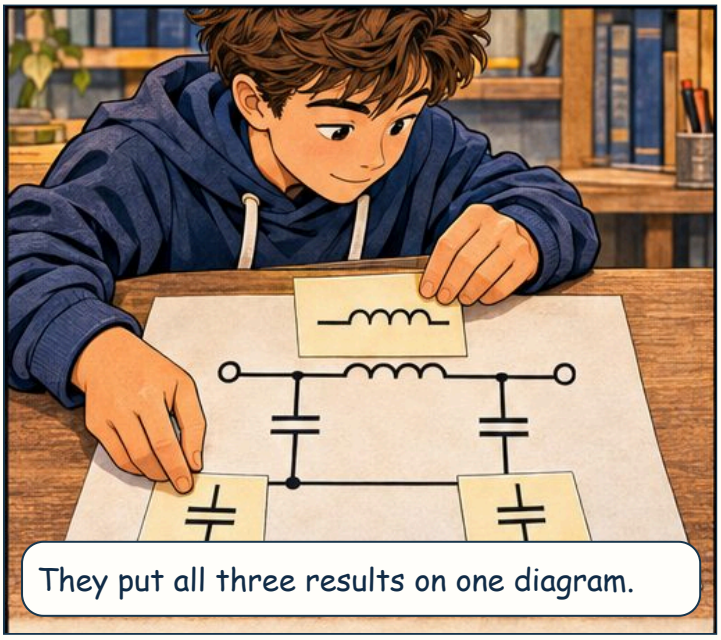
The denominator is $2\pi \times 10\,000\,000$, about $6.283 \times 10^{7}\ s^{-1}$.



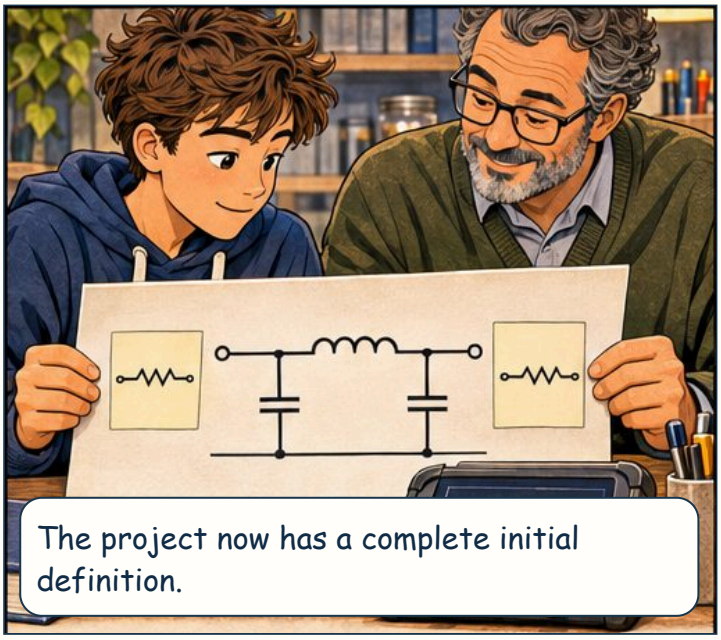
The result is about 1.592×10^{-6} H.



The ideal coil therefore has about 1.59 μH of inductance.

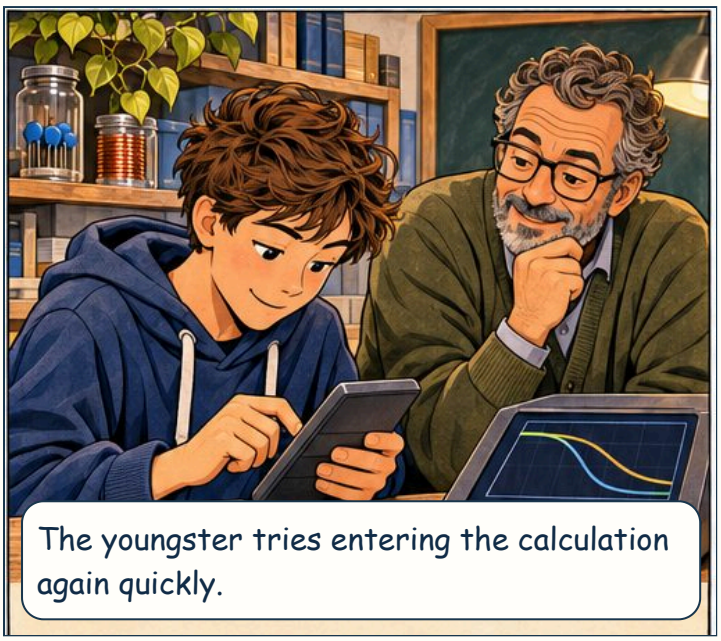


They put all three results on one diagram.

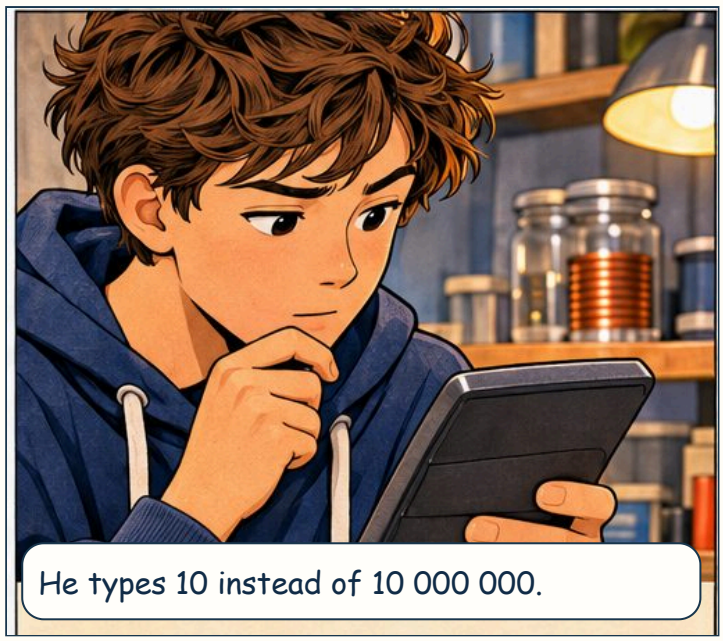


The project now has a complete initial definition.

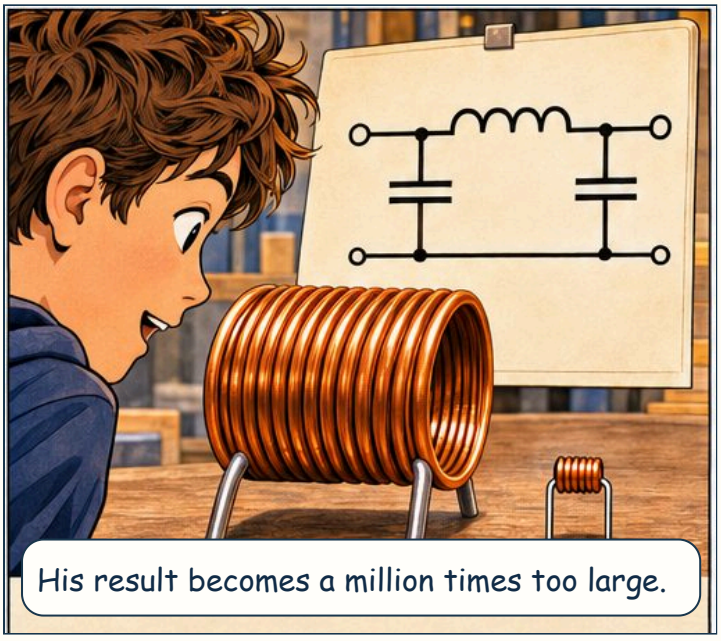
The million-fold mistake



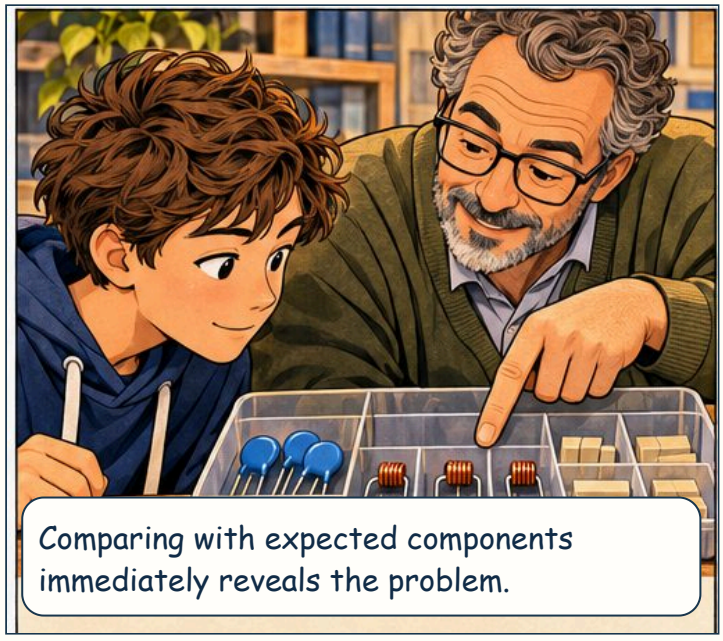
The youngster tries entering the calculation again quickly.



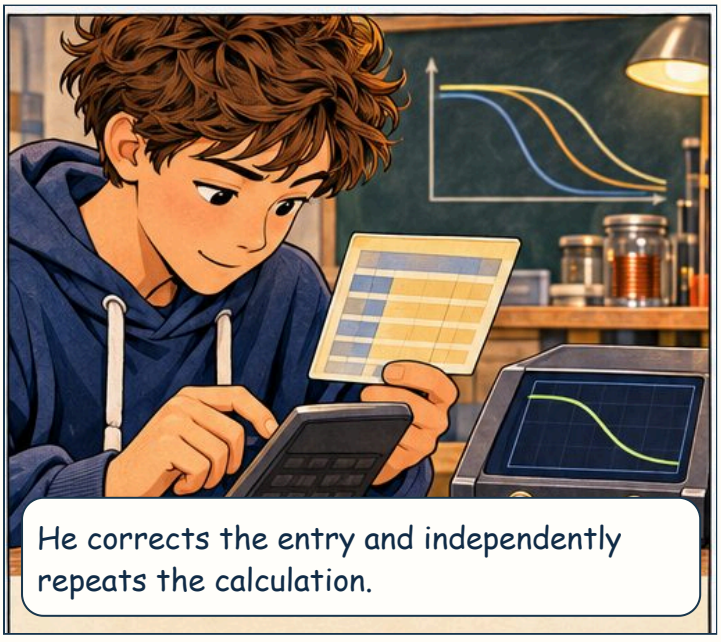
He types 10 instead of 10 000 000.



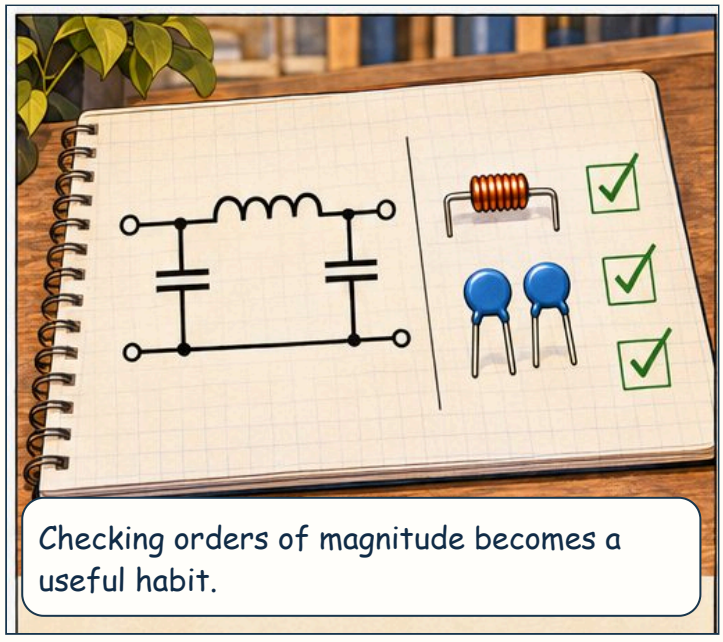
His result becomes a million times too large.



Comparing with expected components immediately reveals the problem.

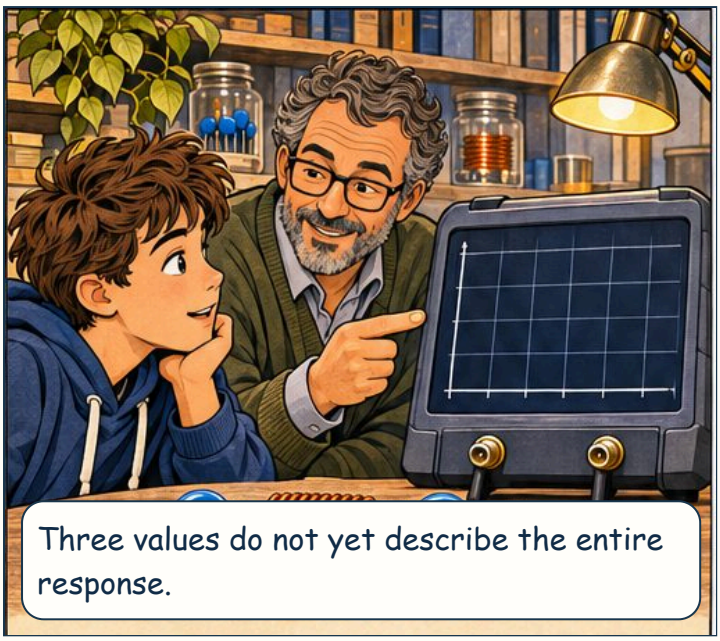


He corrects the entry and independently repeats the calculation.

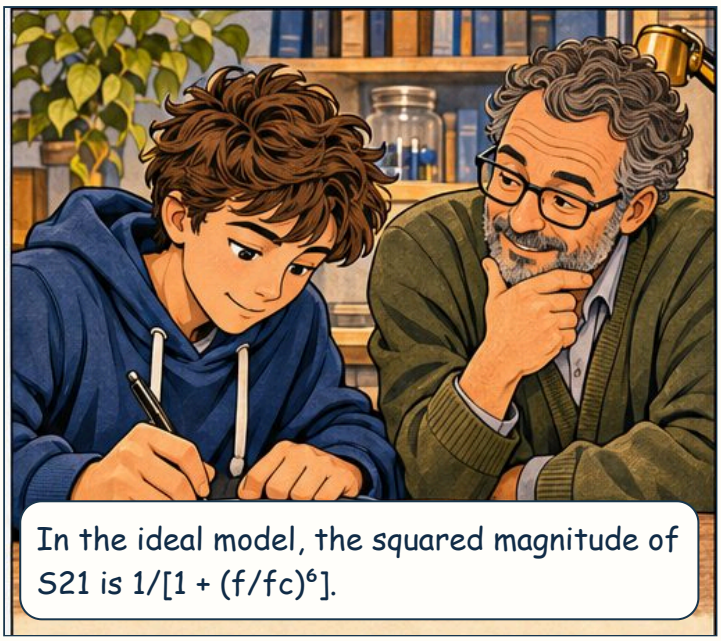


Checking orders of magnitude becomes a useful habit.

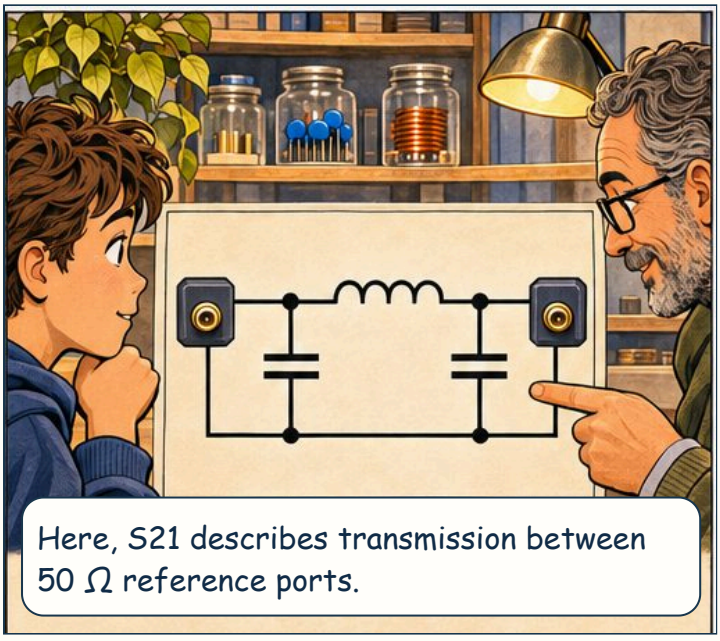
Predicting a whole curve



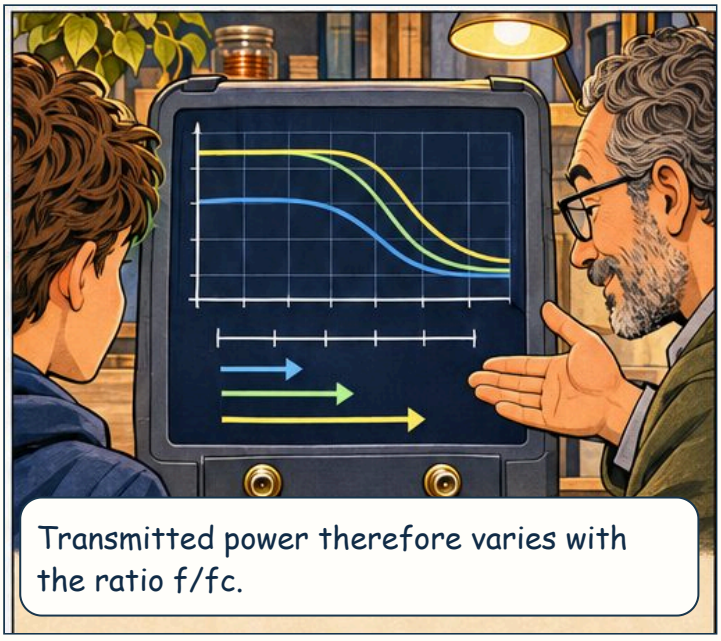
Three values do not yet describe the entire response.



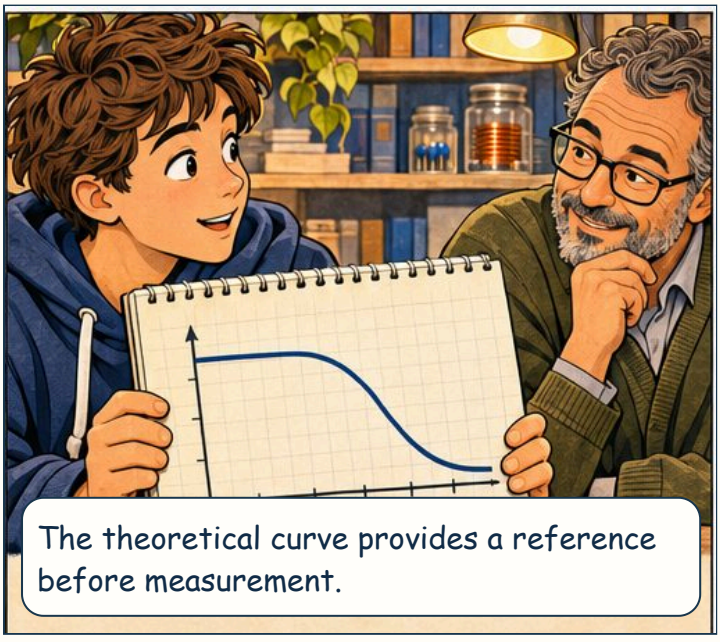
In the ideal model, the squared magnitude of S21 is $1/[1 + (f/fc)^6]$.



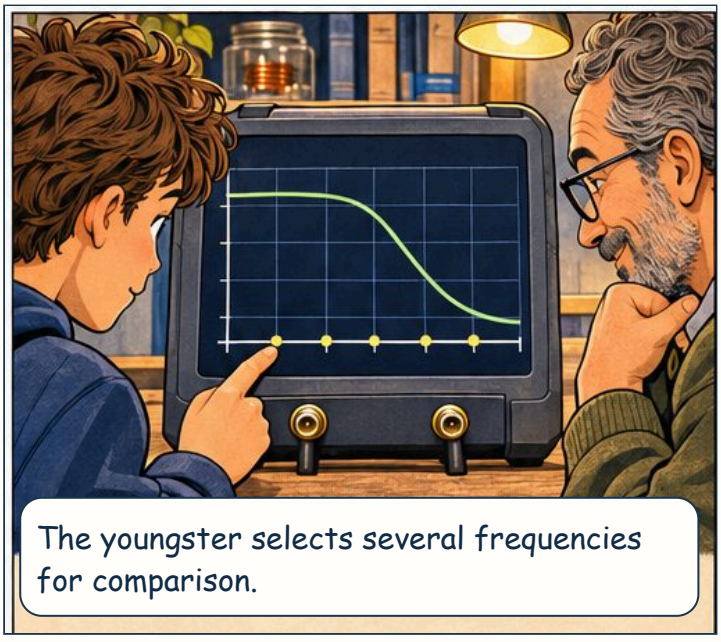
Here, S21 describes transmission between 50 Ω reference ports.



Transmitted power therefore varies with the ratio f/fc.



The theoretical curve provides a reference before measurement.



The youngster selects several frequencies for comparison.

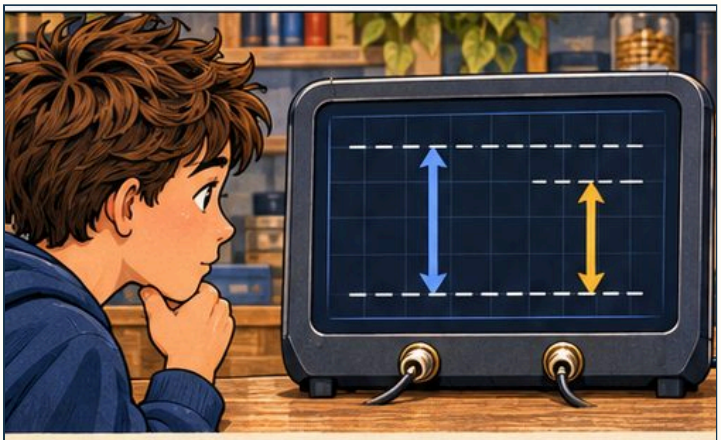
What does minus three decibels mean?



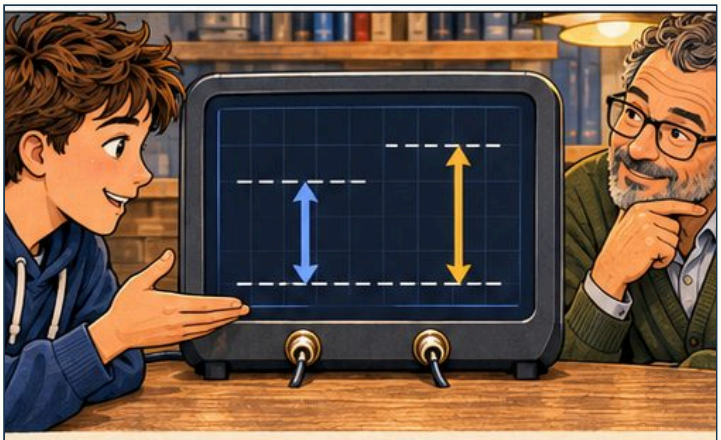
At f = fc, the ideal transmitted power ratio is 1/2.



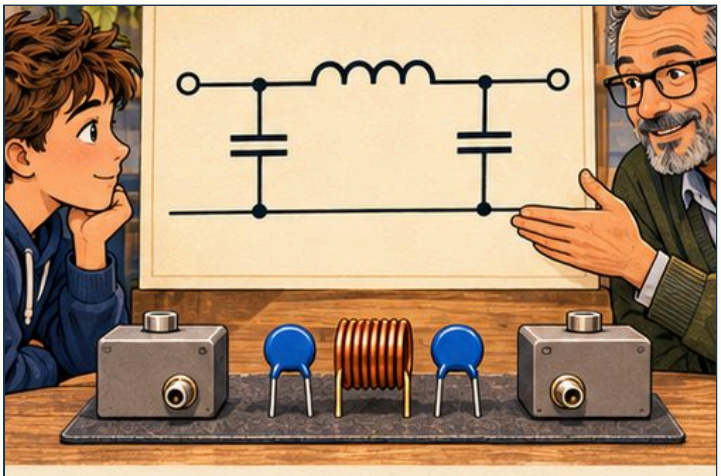
In decibels, 10 log10(1/2) gives about −3.01 dB.



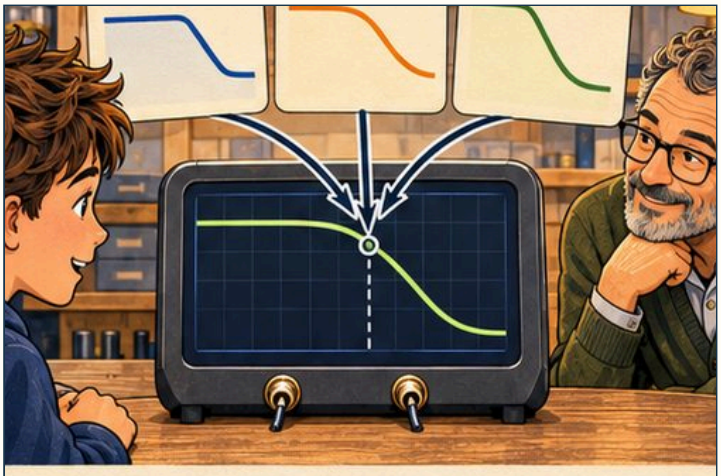
The magnitude of S21 is then about 0.707.



This amplitude is therefore not one half.



The calculation uses appropriate 50 Ω references.

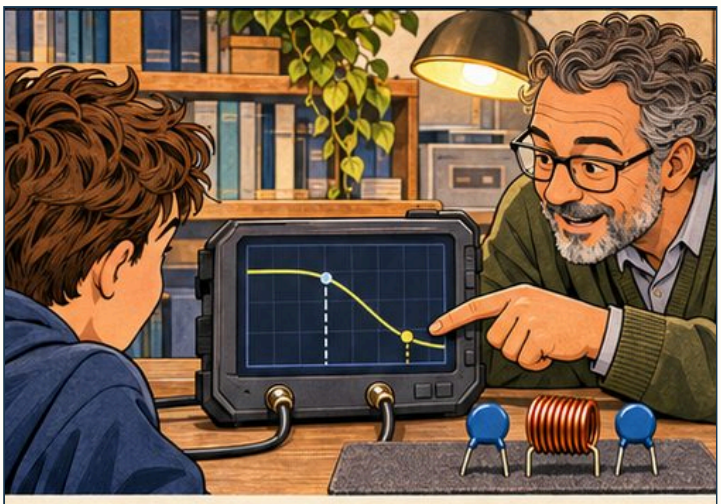


The youngster connects three ways of expressing the same curve point.

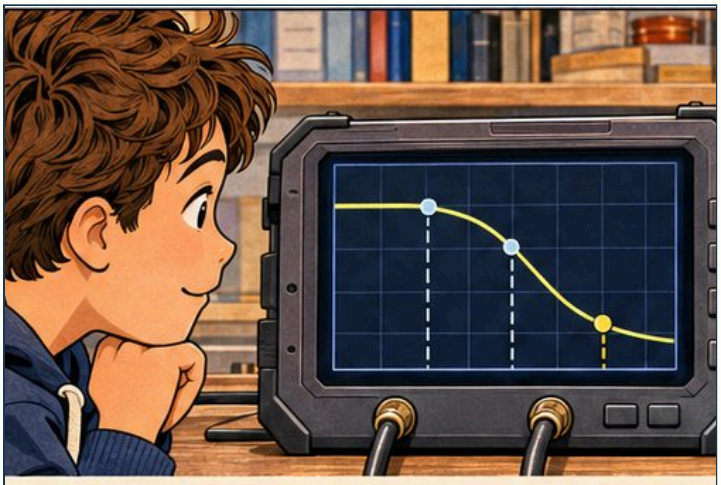
Beyond cutoff



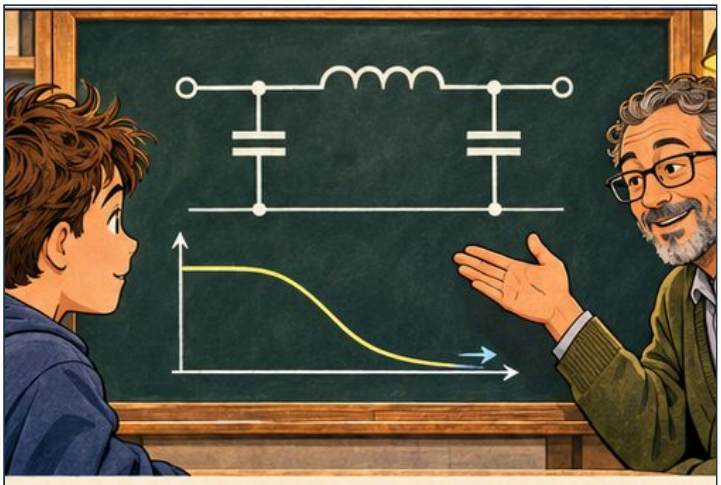
At 20 MHz, f/fc is 2.



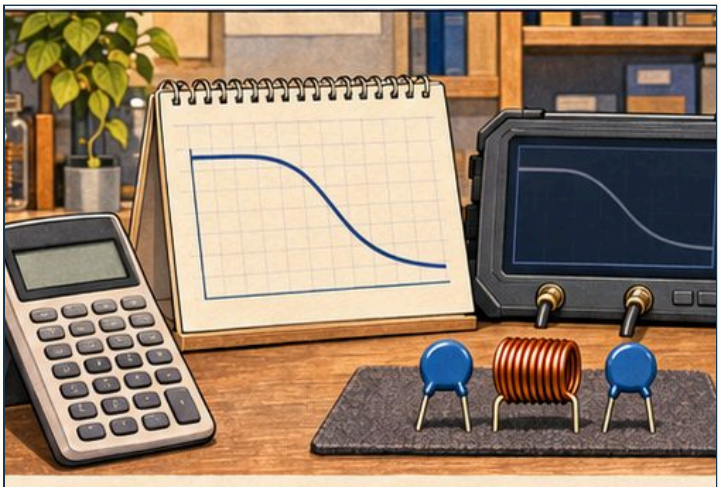
Ideal transmission becomes about −18.13 dB.



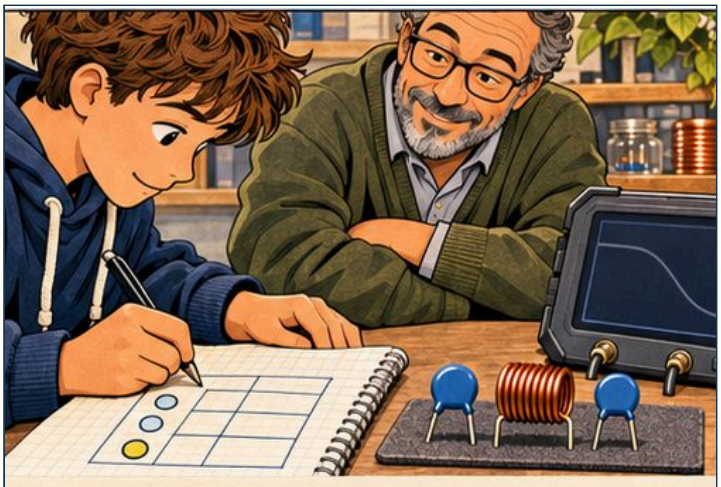
At 30 MHz, f/fc is 3: about −28.63 dB.



Attenuation increases but remains finite.

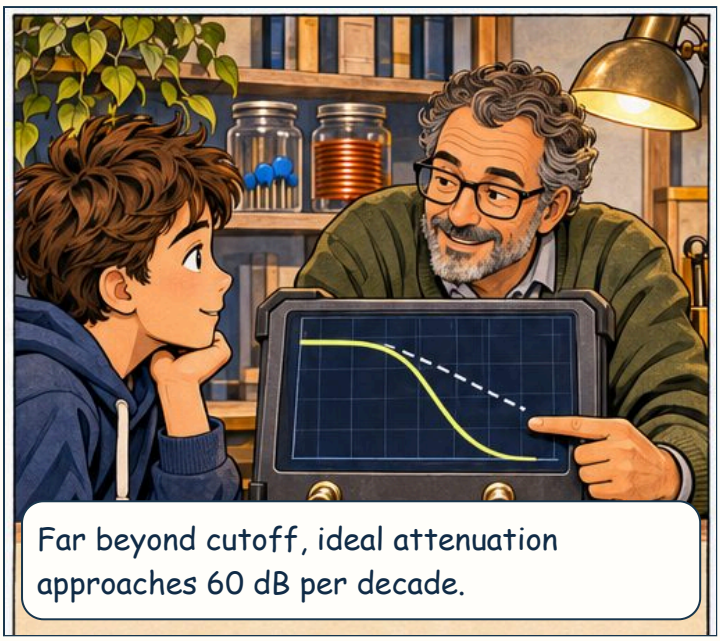


These numbers are calculated, not measured on their circuit.

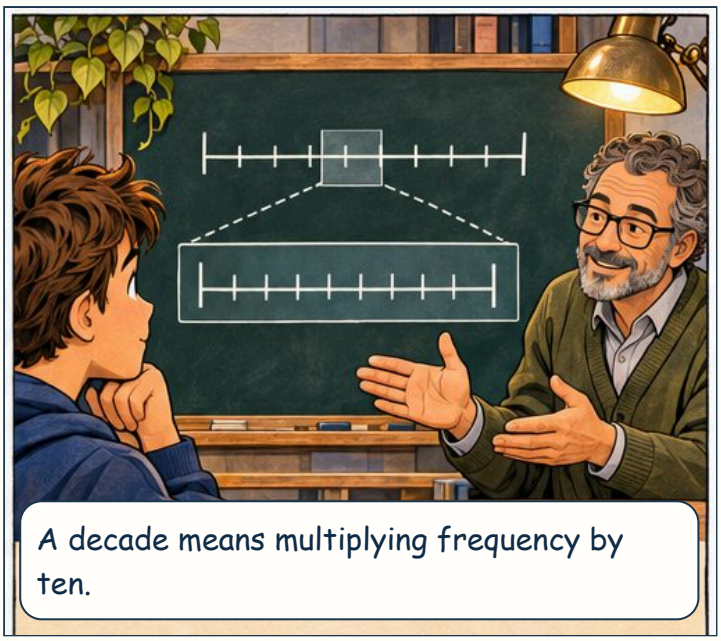


The youngster enters them in the predictions column.

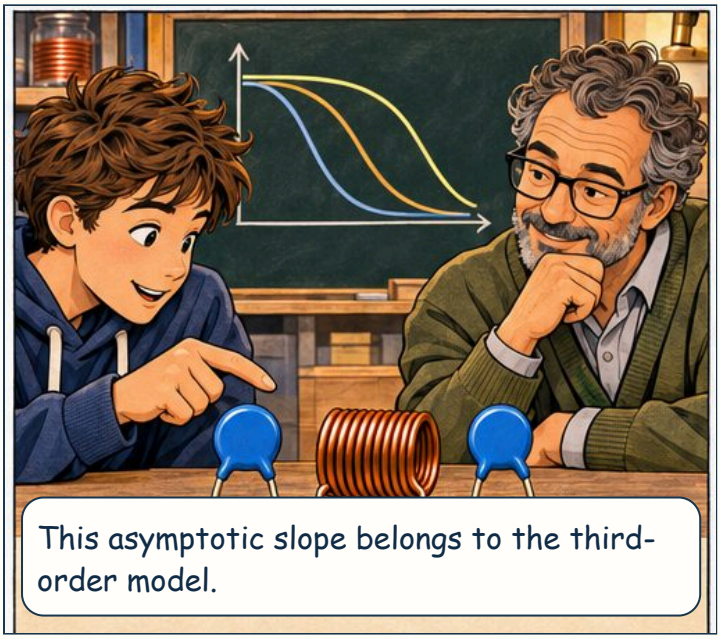
A slope is not a promise



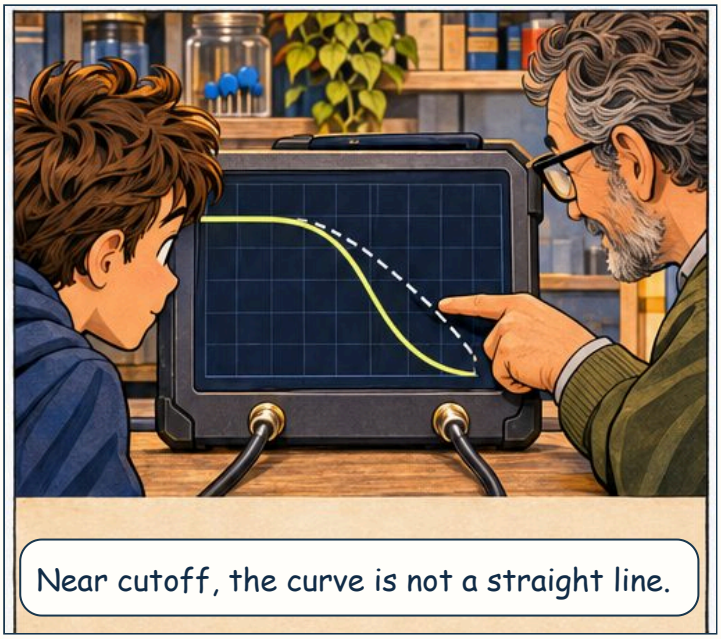
Far beyond cutoff, ideal attenuation approaches 60 dB per decade.



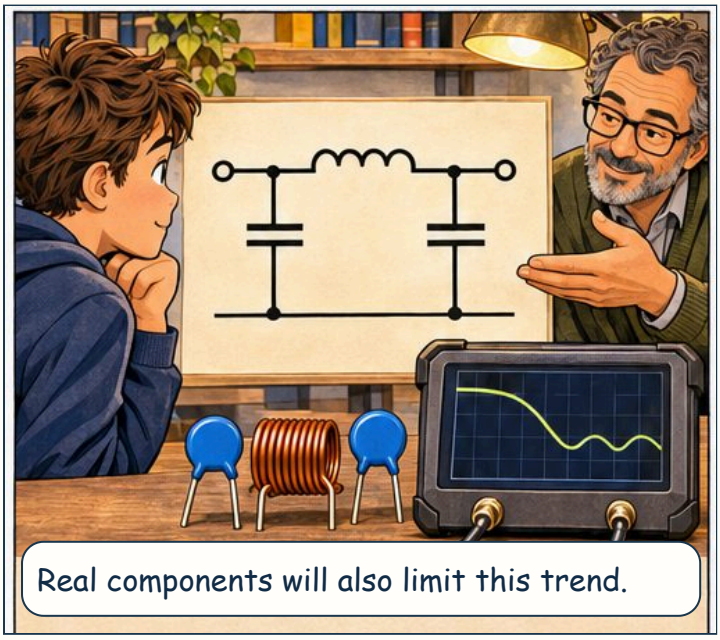
A decade means multiplying frequency by ten.



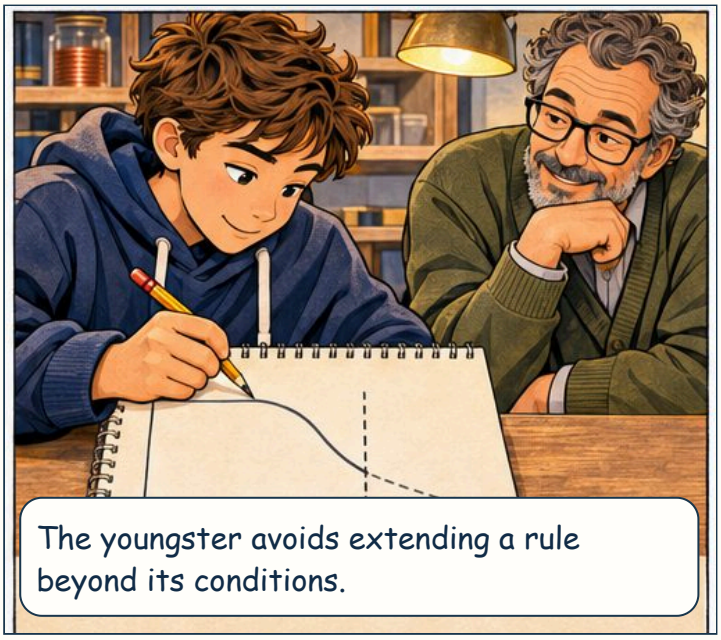
This asymptotic slope belongs to the third-order model.



Near cutoff, the curve is not a straight line.

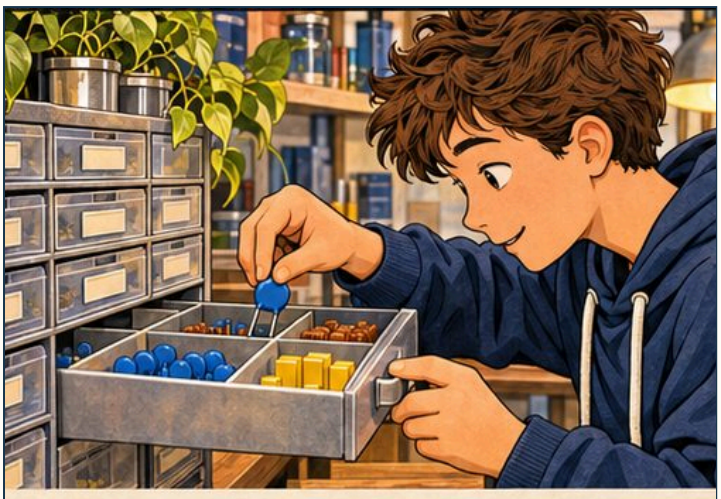


Real components will also limit this trend.

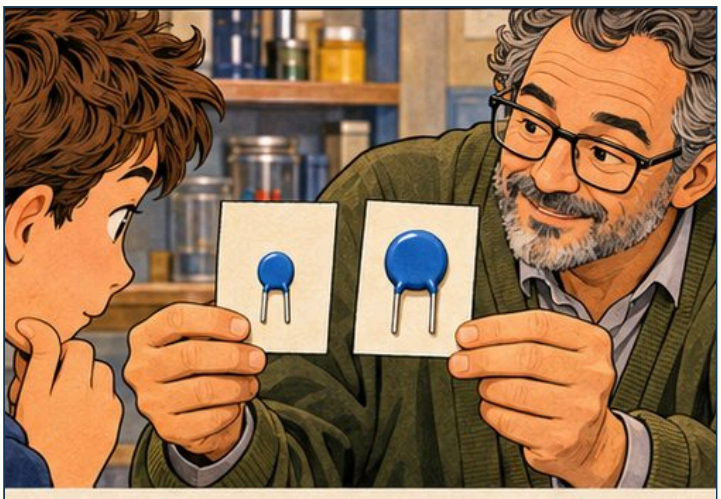


The youngster avoids extending a rule beyond its conditions.

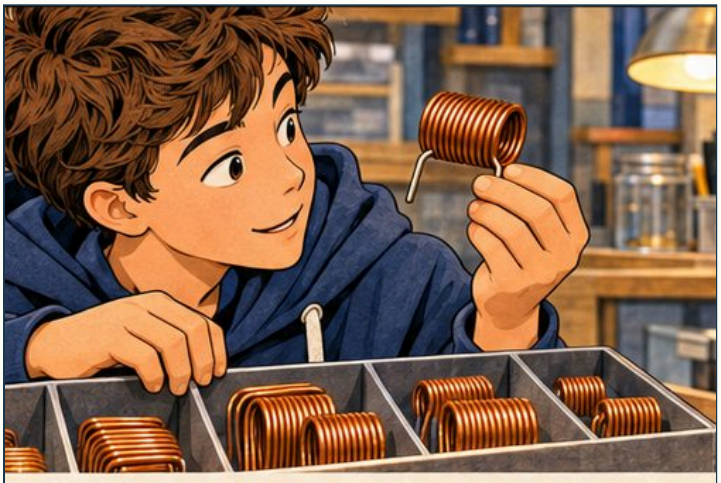
Available component values



The drawer may not contain 318.3 pF capacitors.



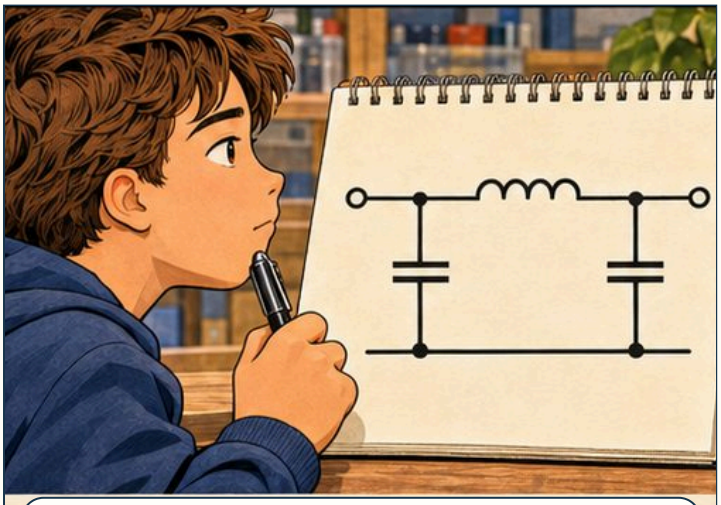
A common 330 pF value is not identical.



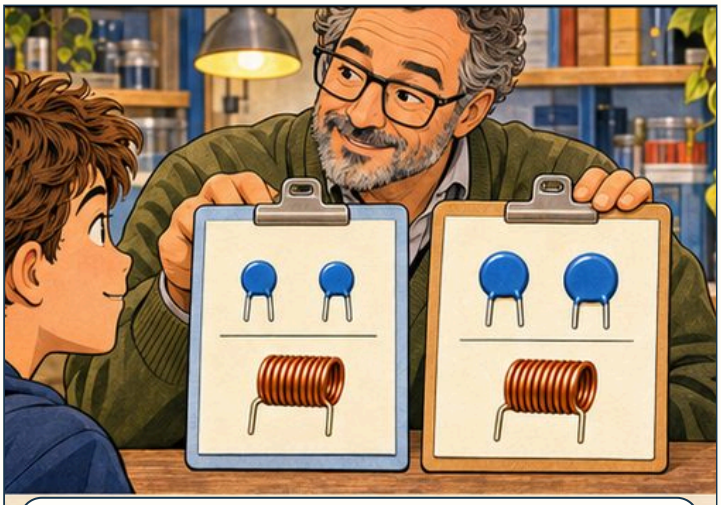
A 1.6 µH coil approaches their calculated value.



Choosing these values requires recalculation or simulation of the response.

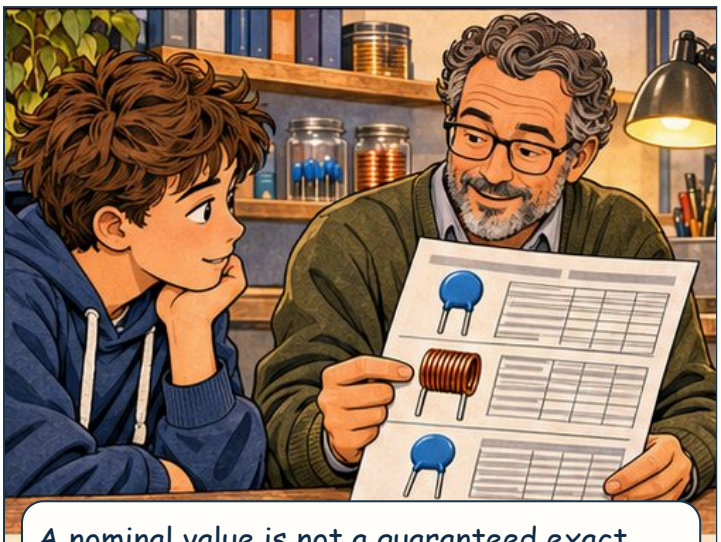


This circuit cannot automatically be called “exactly 10 MHz”.



The youngster keeps ideal and selected values separate.

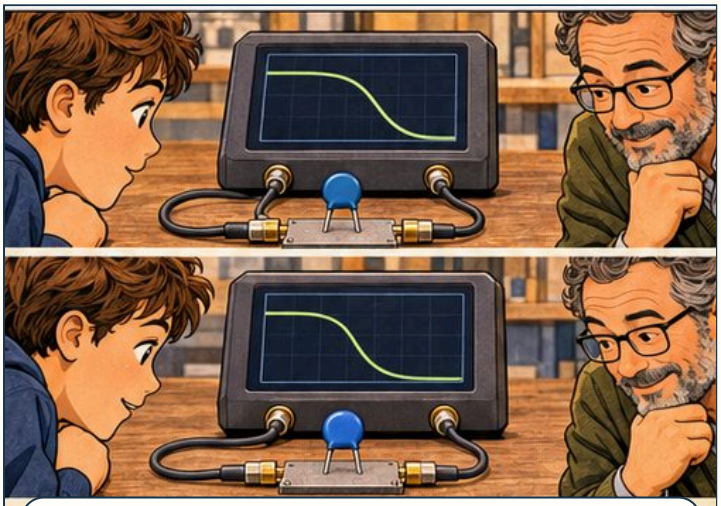
Every part has a tolerance



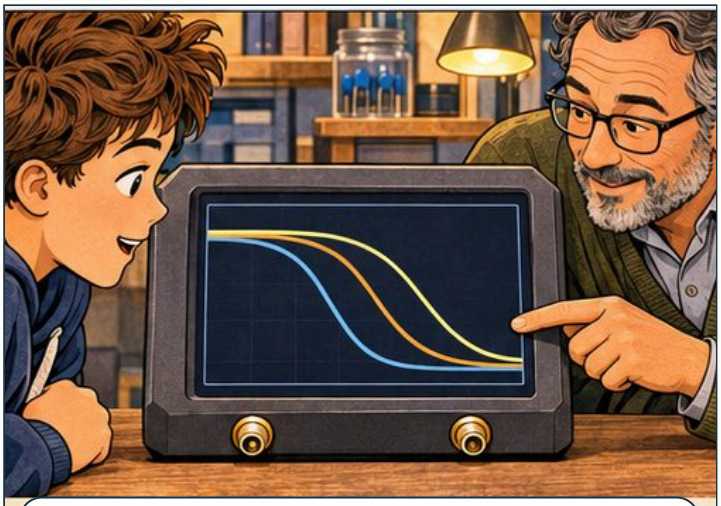
A nominal value is not a guaranteed exact value.



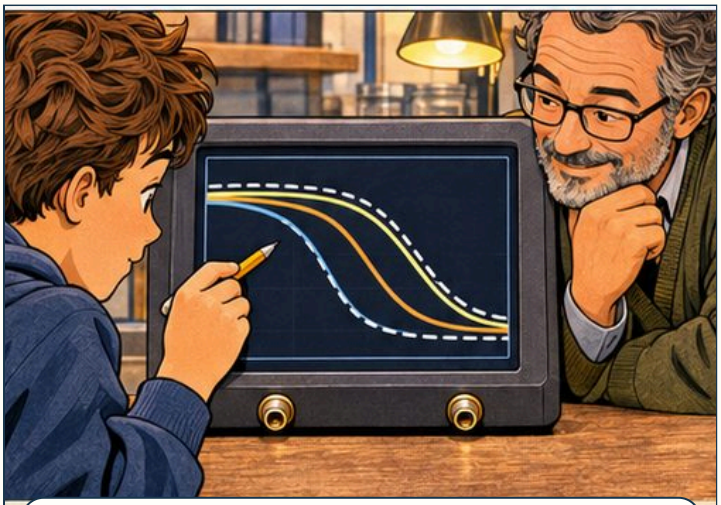
Capacitor and coil tolerances matter.



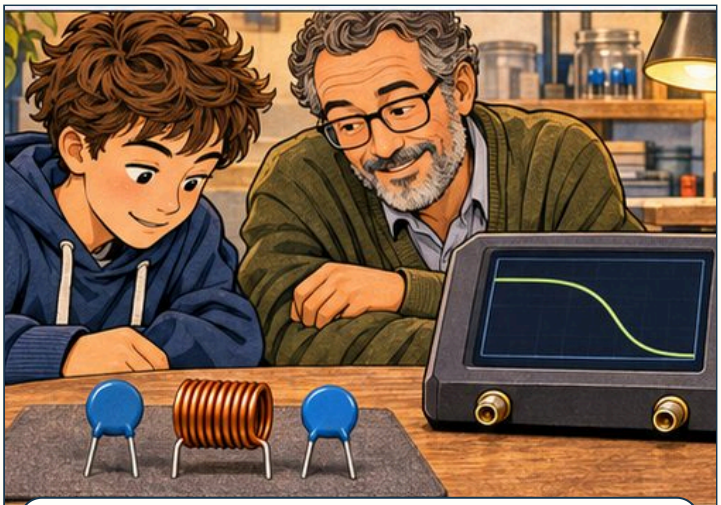
Components with identical markings can differ slightly.



Simulation can explore several combinations of values.



It helps predict a range of possible responses.



Measurements will then examine the actual parts used.

Hidden components



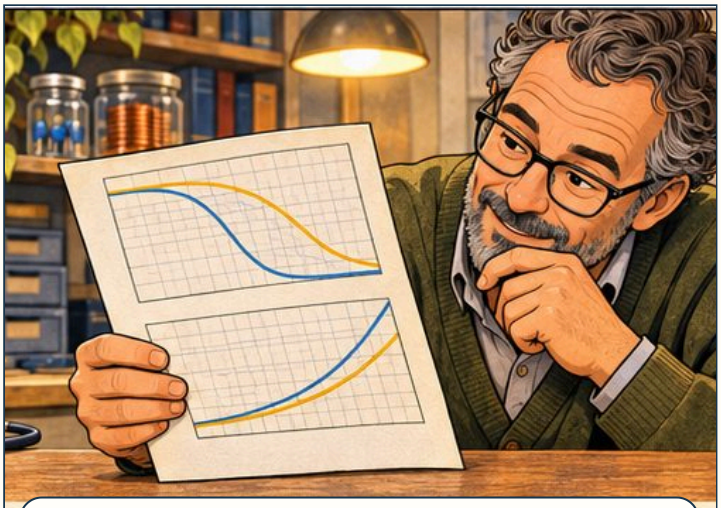
A real coil also has resistance and parasitic capacitance.



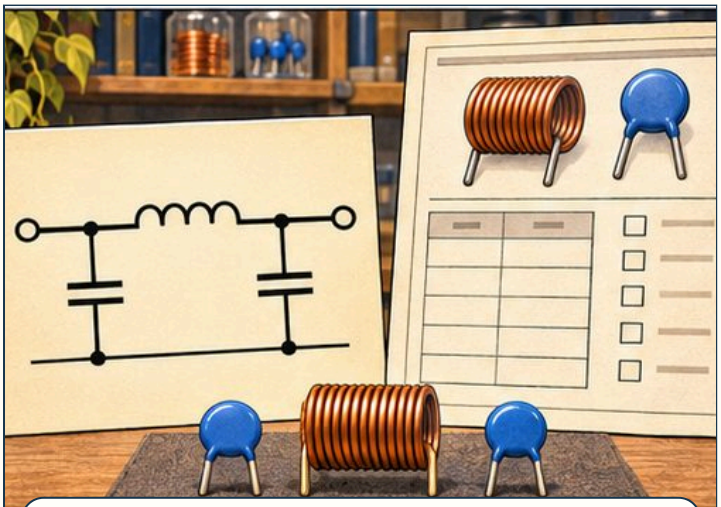
A capacitor has losses and parasitic inductance, among other effects.



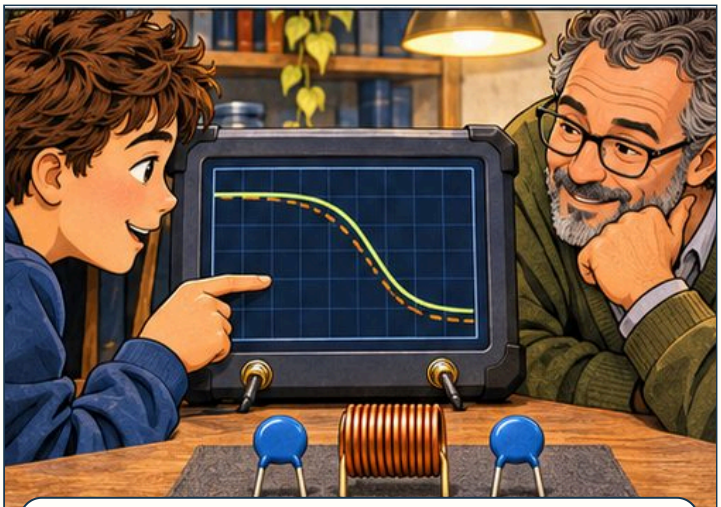
Their behavior changes near certain resonances.



Datasheets specify limits that need checking.

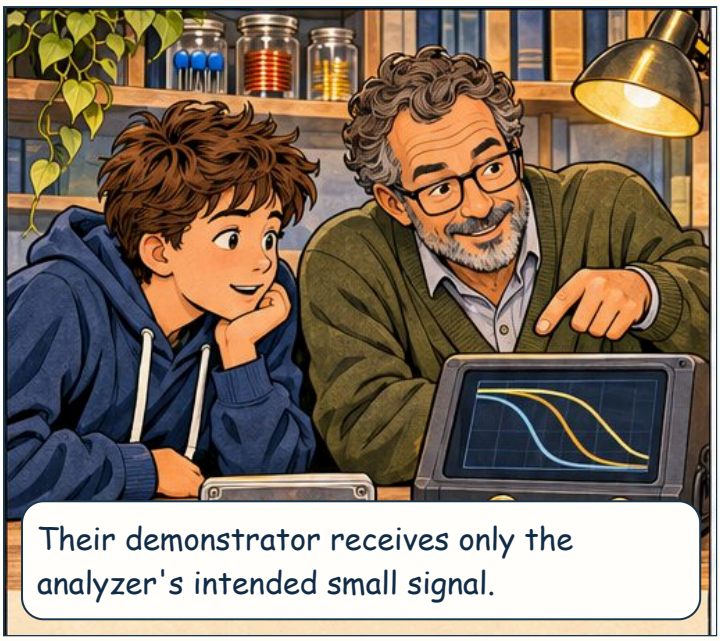


A value in picofarads or microhenrys is therefore insufficient.

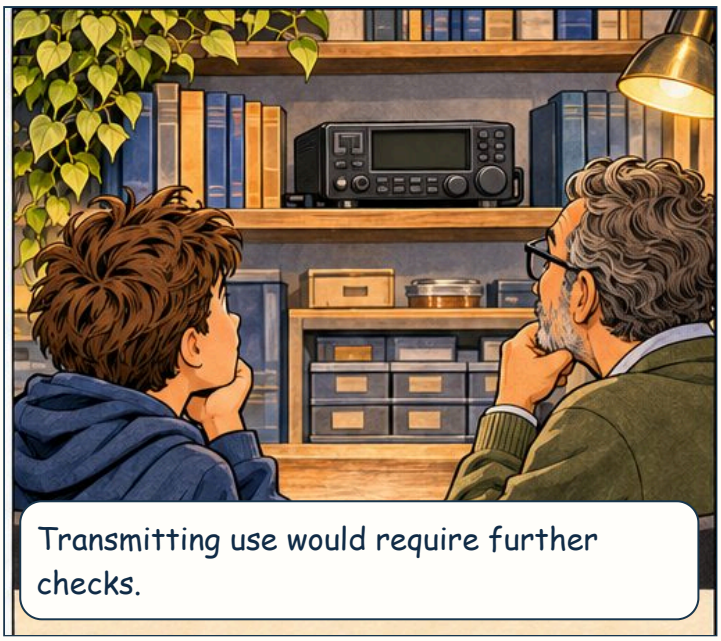


The youngster learns to read beyond the first line.

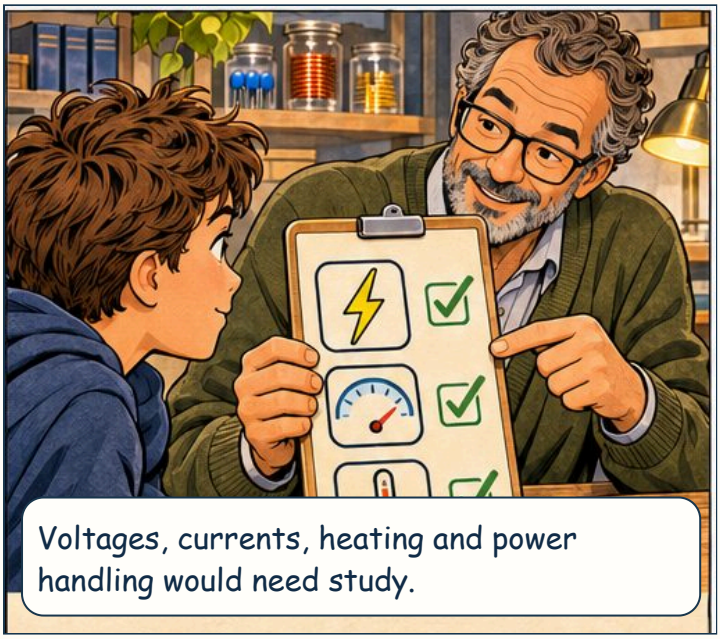
A bench test does not qualify a transmitter



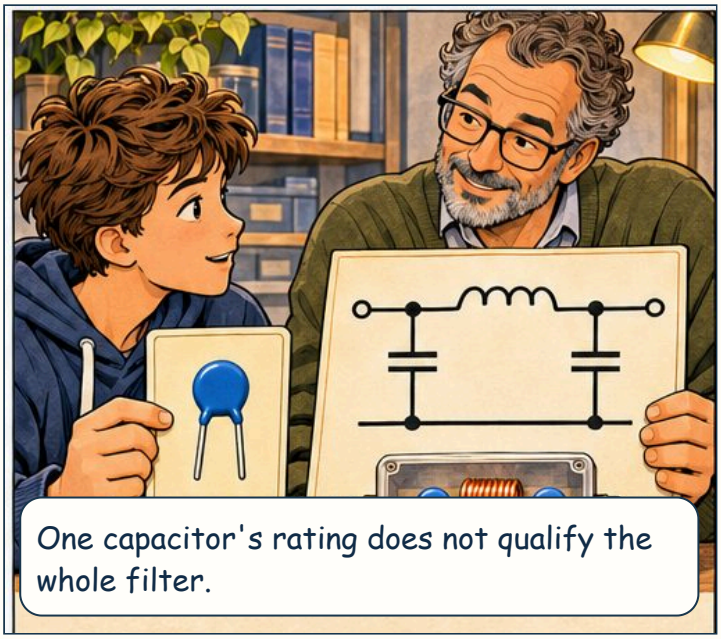
Their demonstrator receives only the analyzer's intended small signal.



Transmitting use would require further checks.



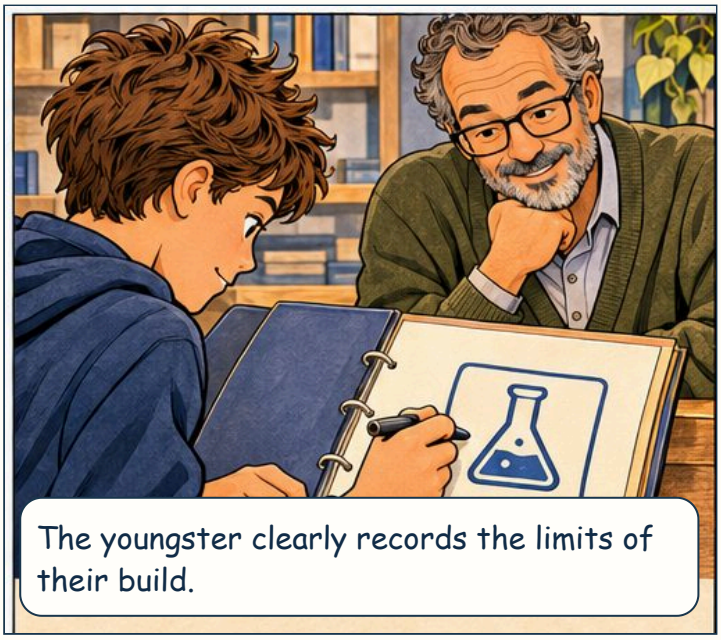
Voltages, currents, heating and power handling would need study.



One capacitor's rating does not qualify the whole filter.

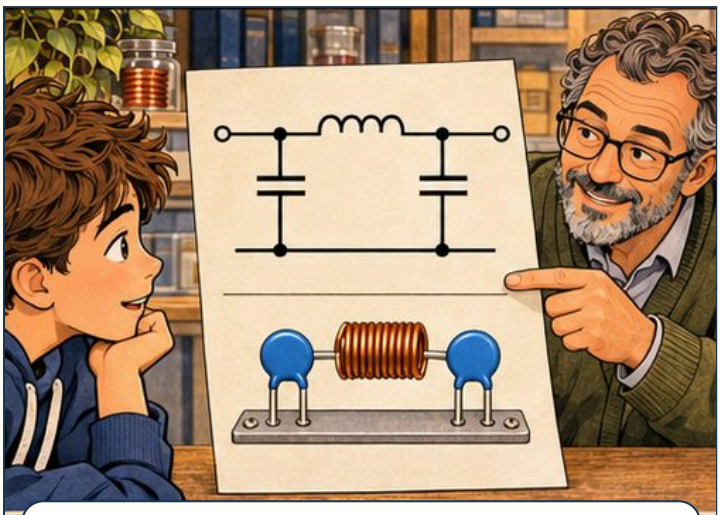


This workshop includes no power tests.

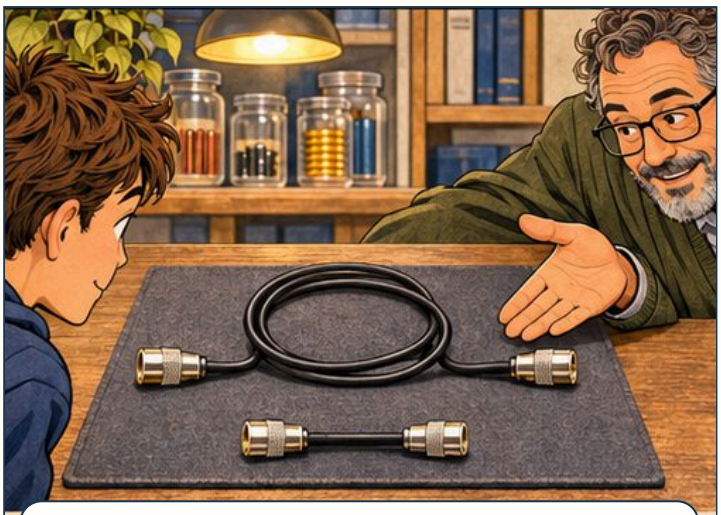


The youngster clearly records the limits of their build.

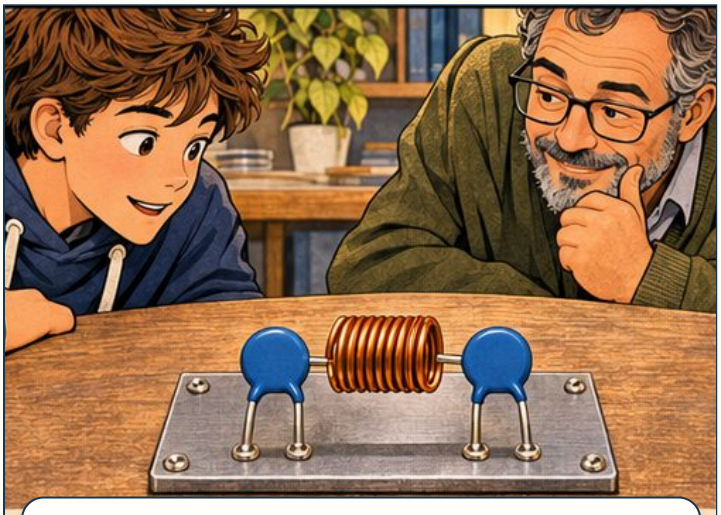
Planning the layout



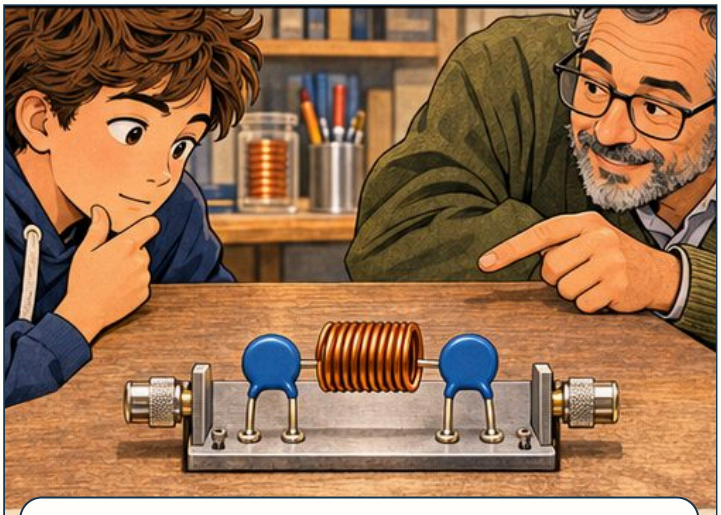
The schematic shows connections, but not their complete geometry.



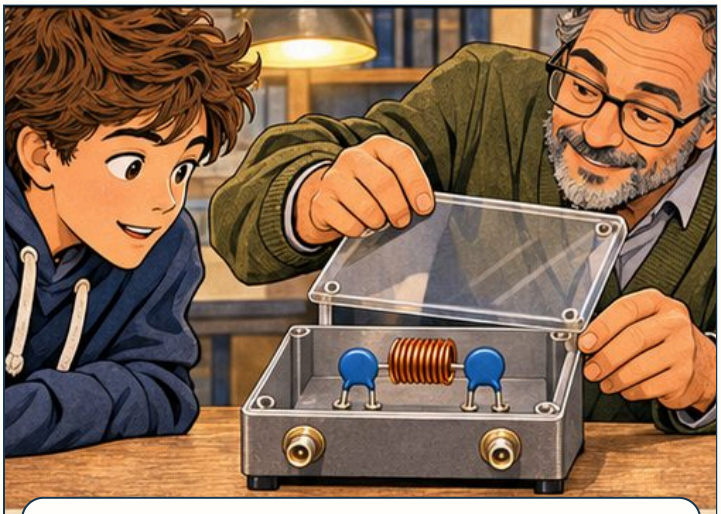
At these frequencies, connection lengths and layout can matter.



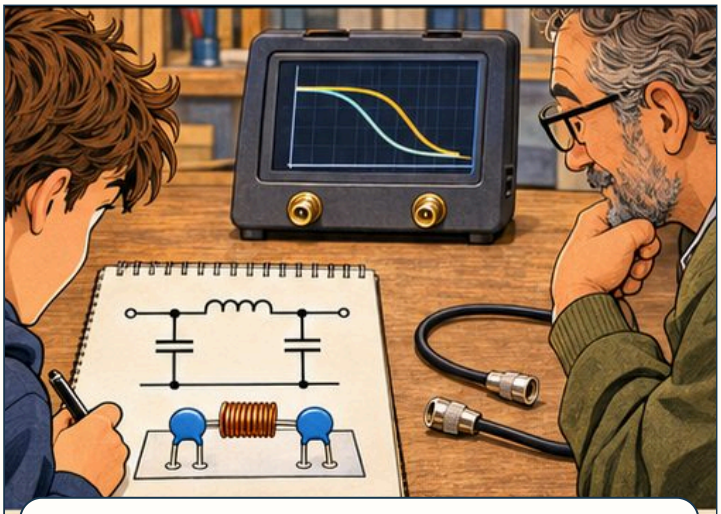
They plan a common ground and short connections.



They also separate paths that could couple directly.



Henri prepares a demonstrator suitable for measurement.

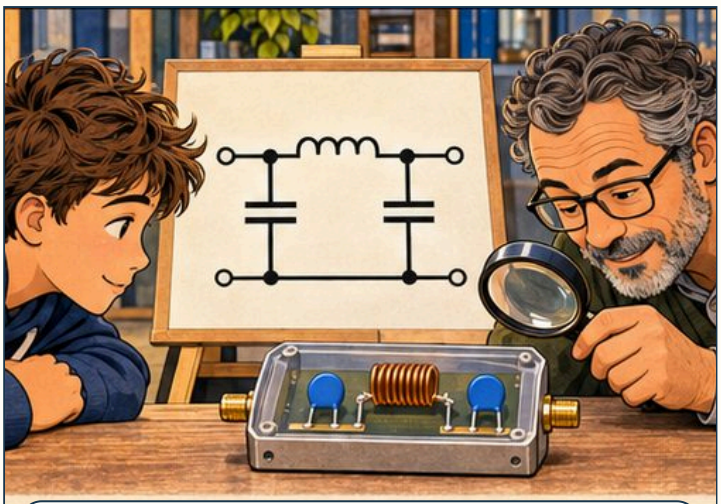


Lucas compares layout and schematic, connection by connection.

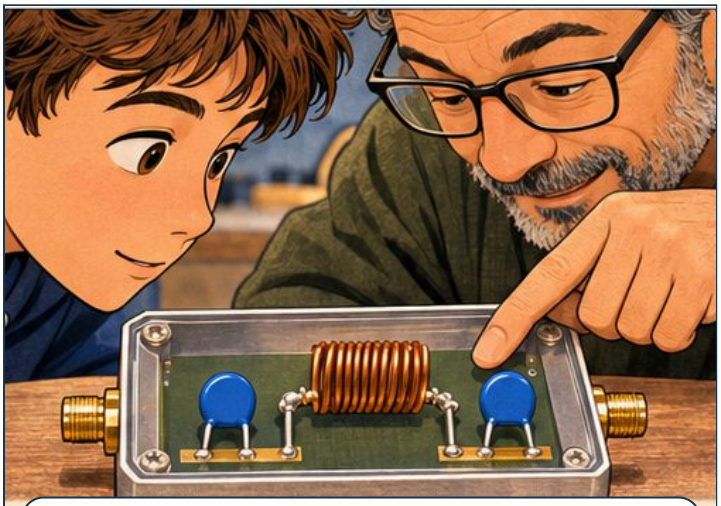
Checking before connecting



The measurement source remains off during preparation.



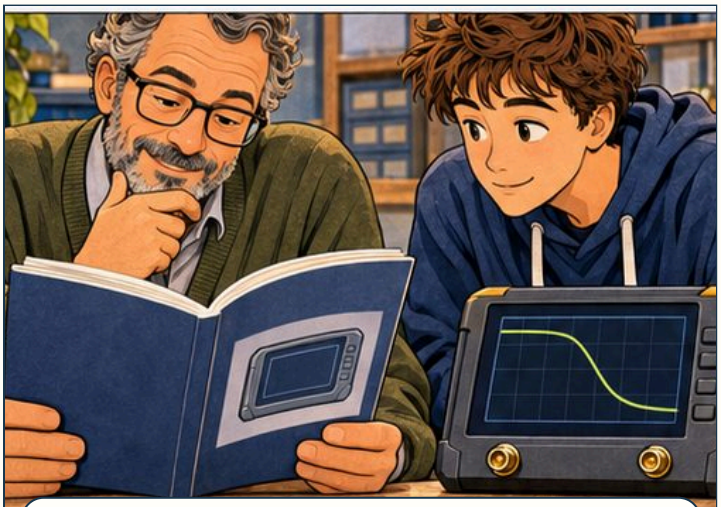
They check connections, components and common ground.



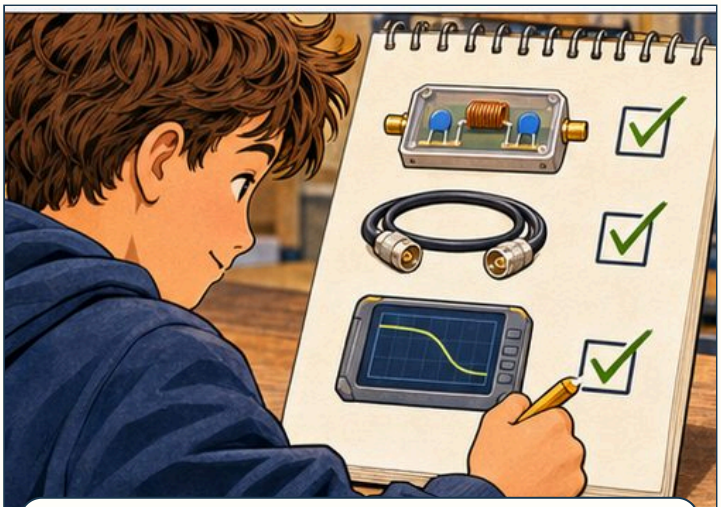
They look for shorts, wiring errors and damaged parts.



Connectors and cables are inspected next.



The mentor checks the instrument's input limits.



The youngster completes his checklist before the first sweep.

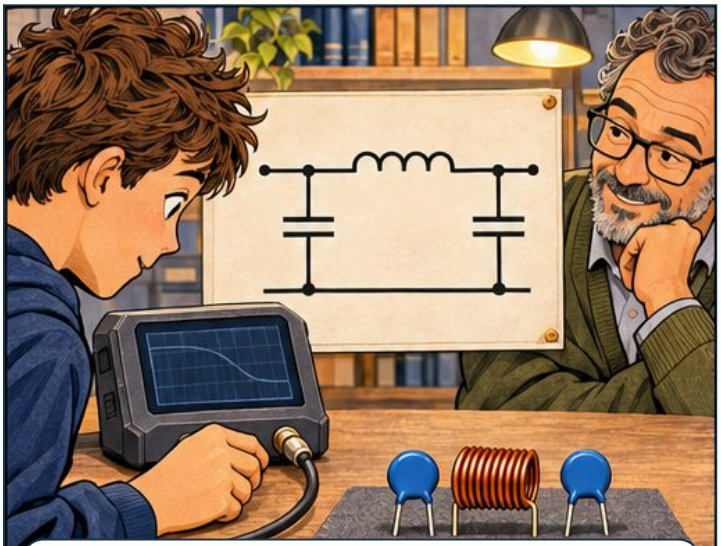
The analyzer asks questions



The network analyzer sends a known small signal.



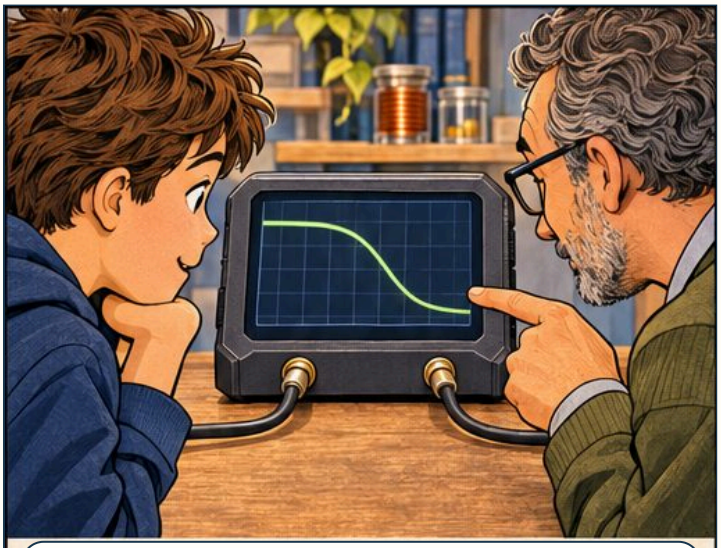
It sweeps a selected frequency range.



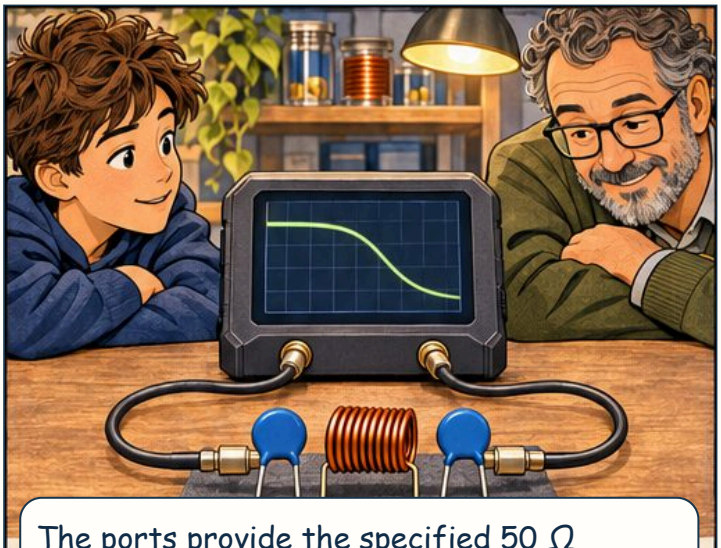
Port 1 feeds the filter input.



Port 2 observes transmission at the output.

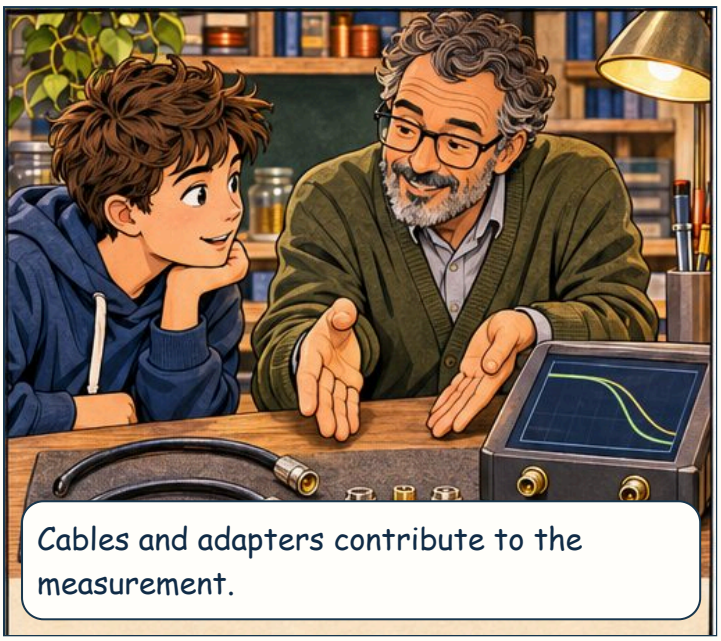


The S21 parameter tracks this transmission.

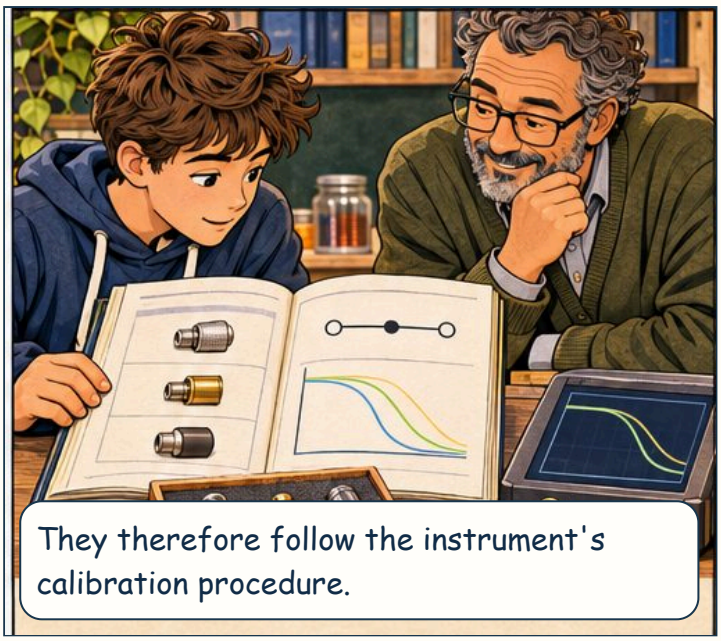


The ports provide the specified 50 Ω references.

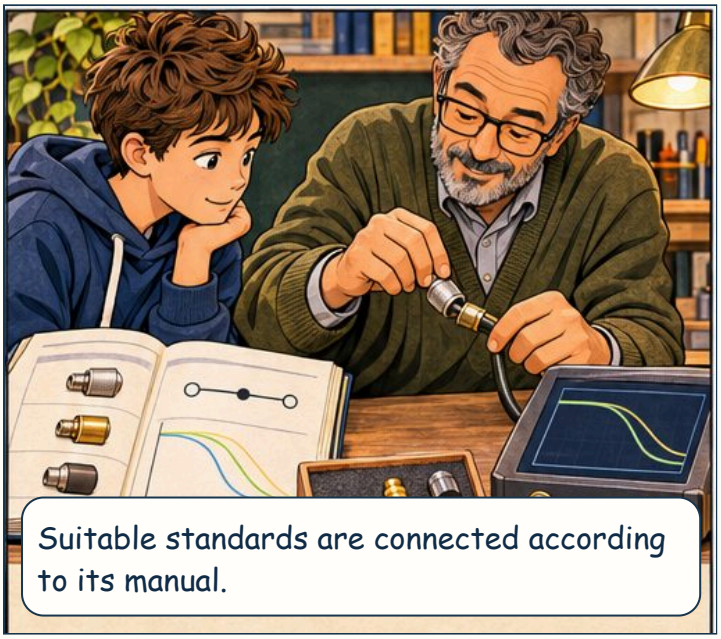
Calibrating in the right place



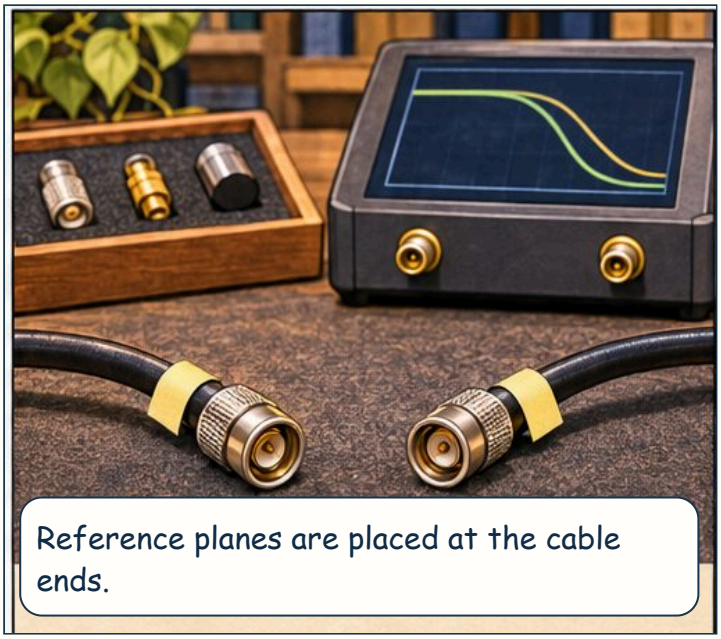
Cables and adapters contribute to the measurement.



They therefore follow the instrument's calibration procedure.



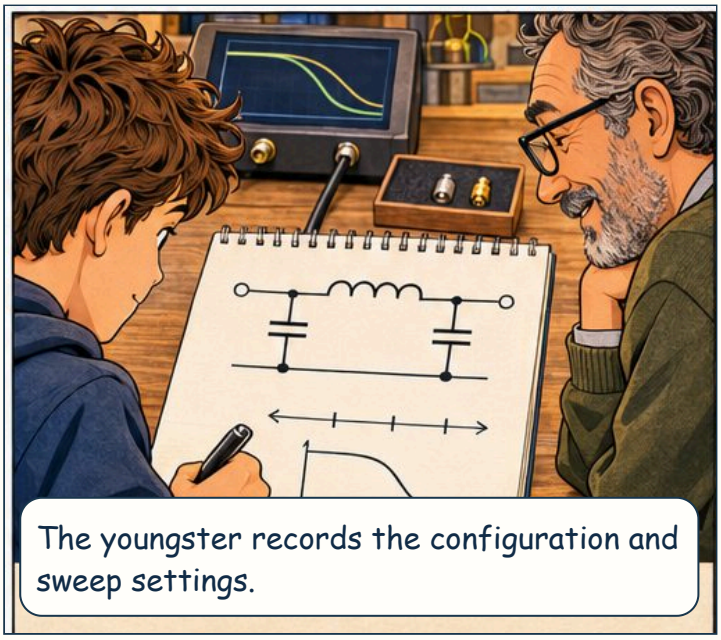
Suitable standards are connected according to its manual.



Reference planes are placed at the cable ends.



After calibration, these connections are preserved where possible.



The youngster records the configuration and sweep settings.

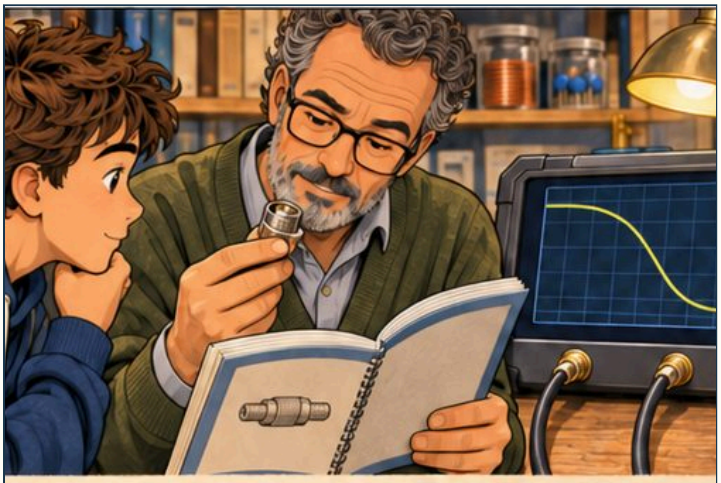
Checking the direct path



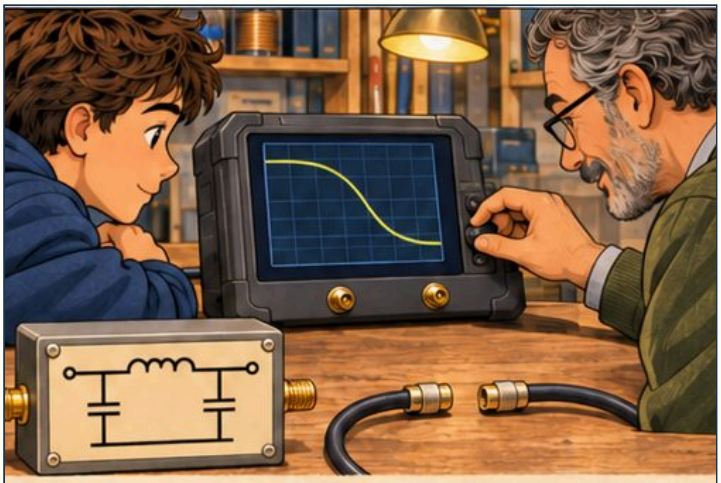
Before inserting the filter, a through connection checks the reference.



Expected transmission must be consistent with that connection.



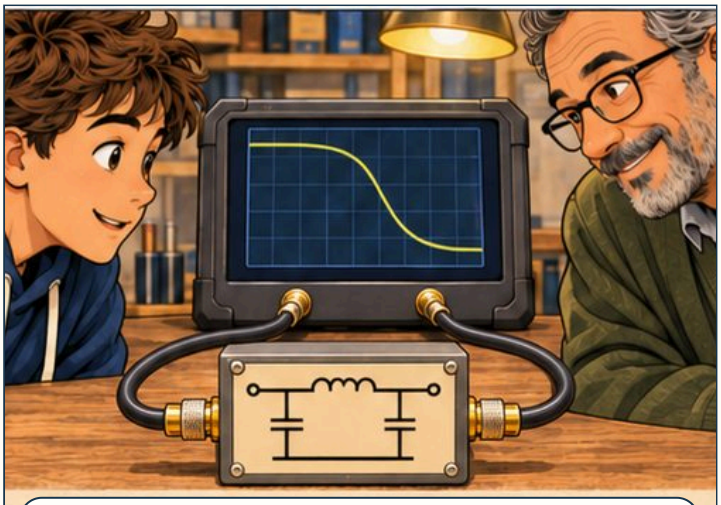
An anomaly requires checking cables, calibration and settings.



A filter should not be adjusted to conceal a bench fault.



After this check, the source is stopped for connection.

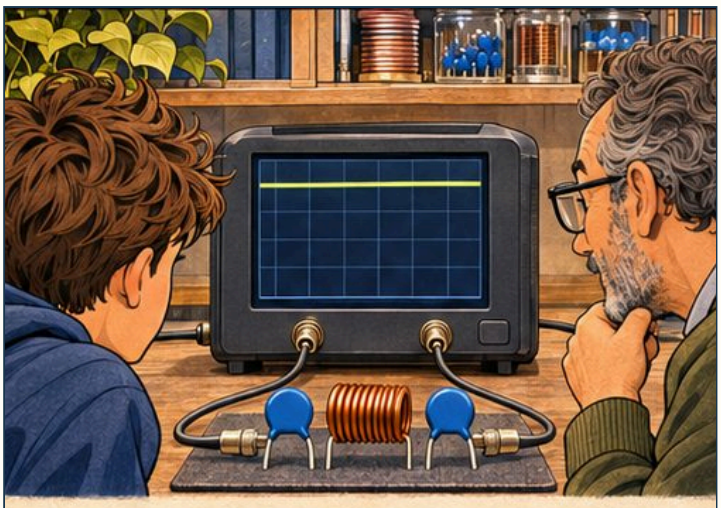


The filter then takes its place between both cables.

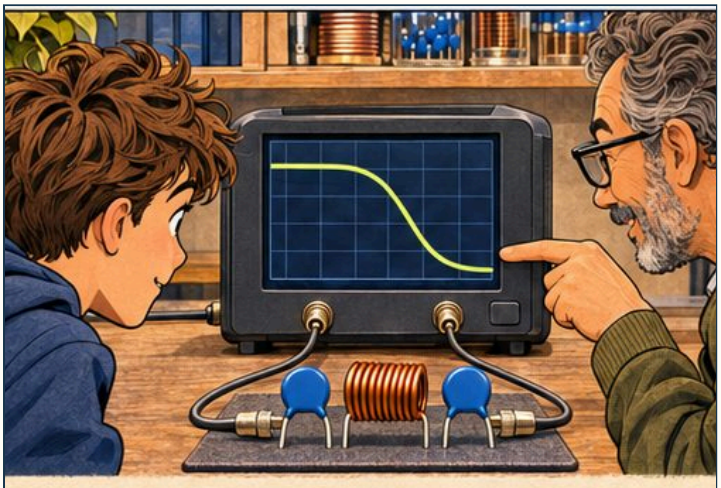
The first sweep



They start a sweep covering the useful band and transition.



The trace stays higher at low frequencies.



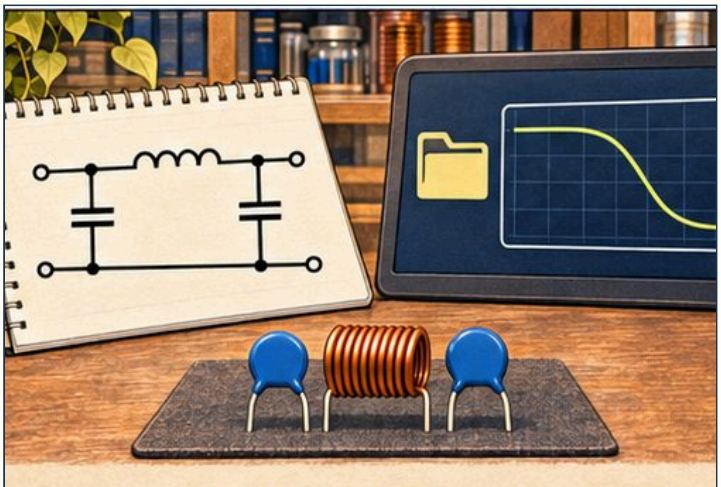
It then falls as frequency increases.



The youngster recognizes the predicted shape without assuming perfect agreement.

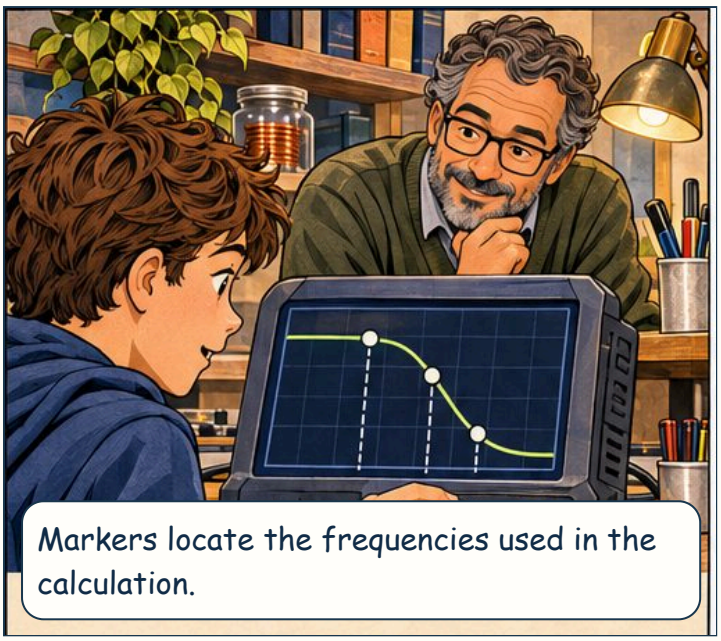


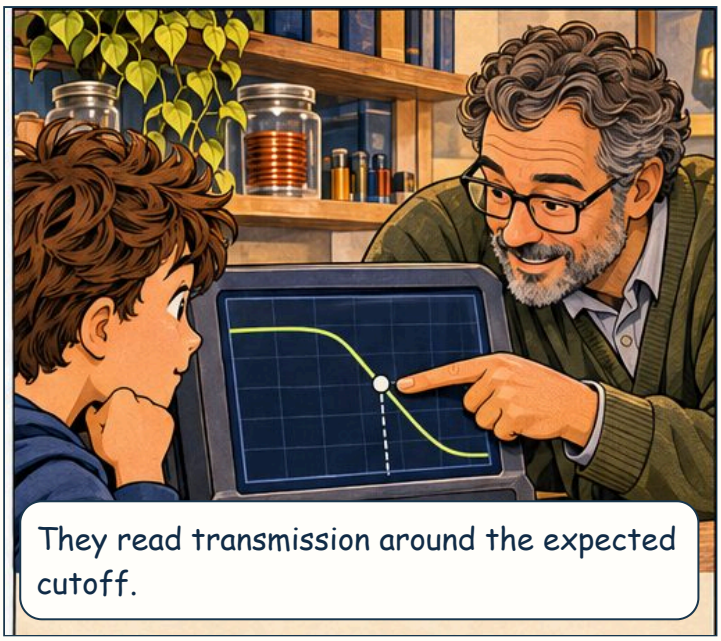
He saves the trace and measurement conditions.

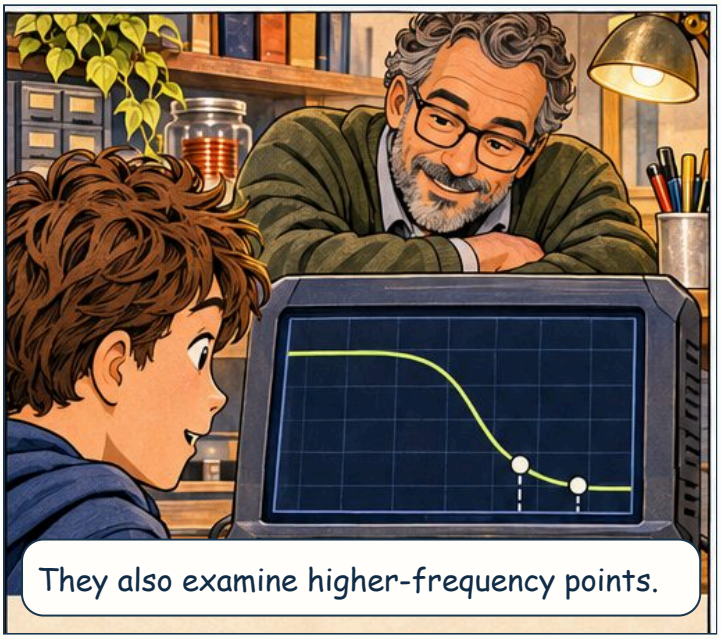


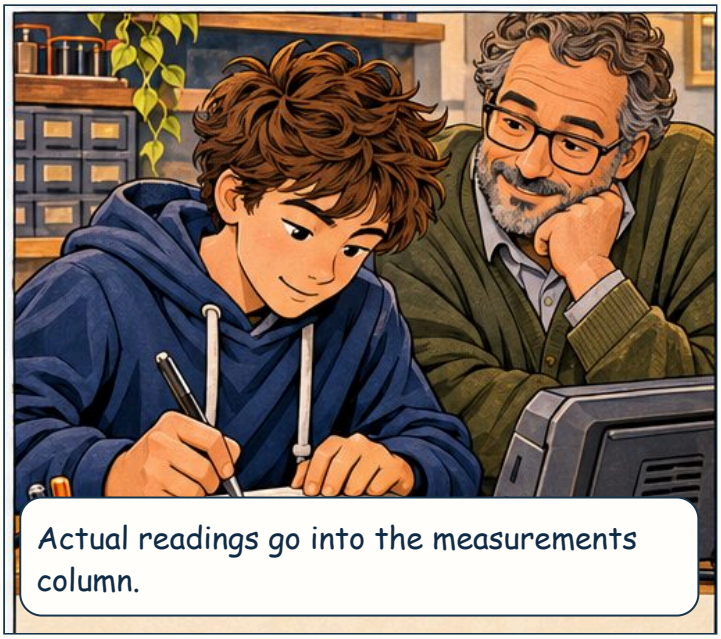
A saved result can be compared after each change.

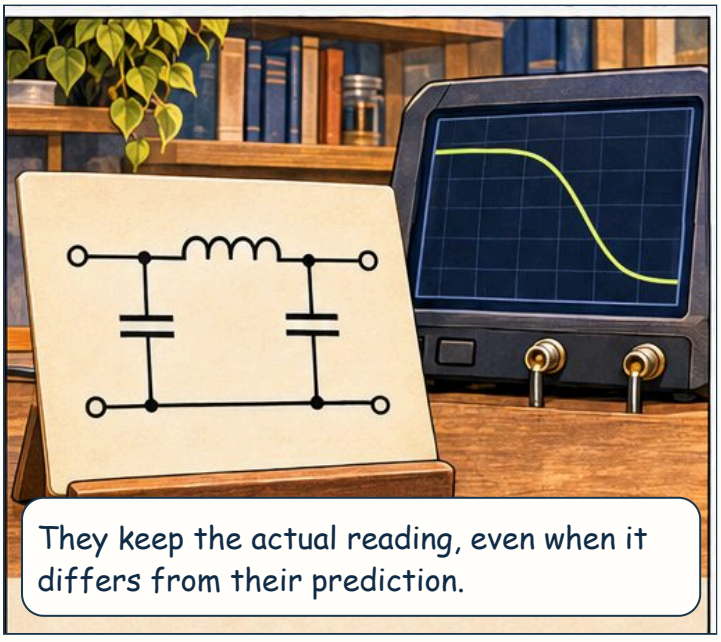
Reading precise points

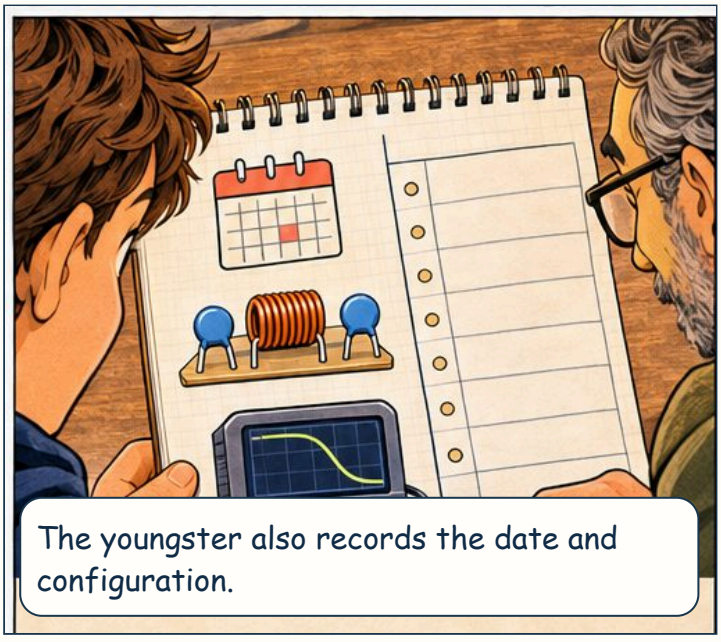




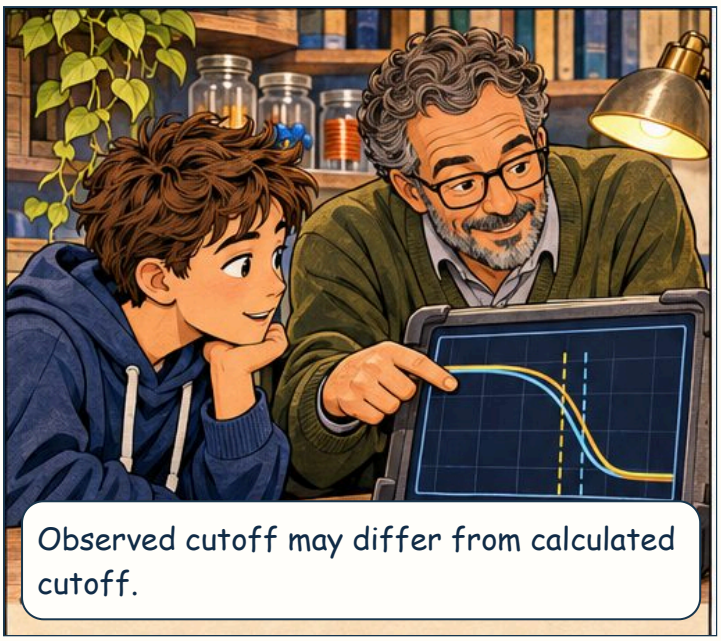




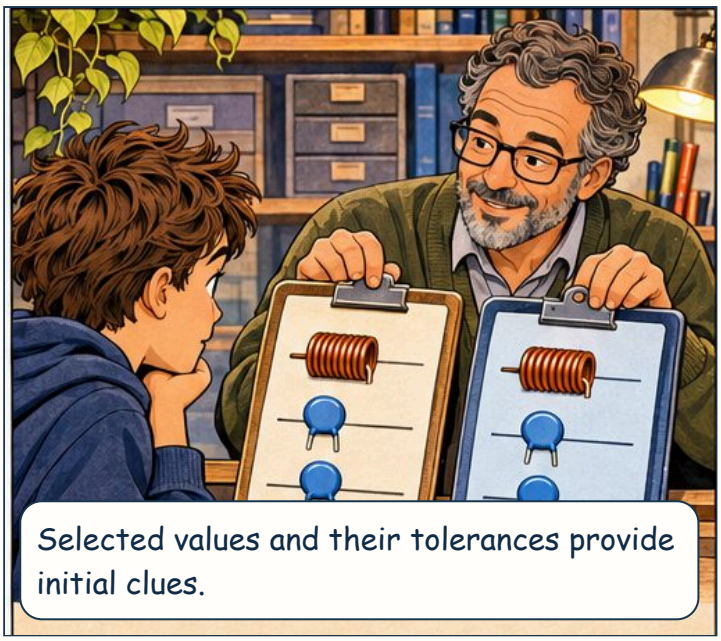




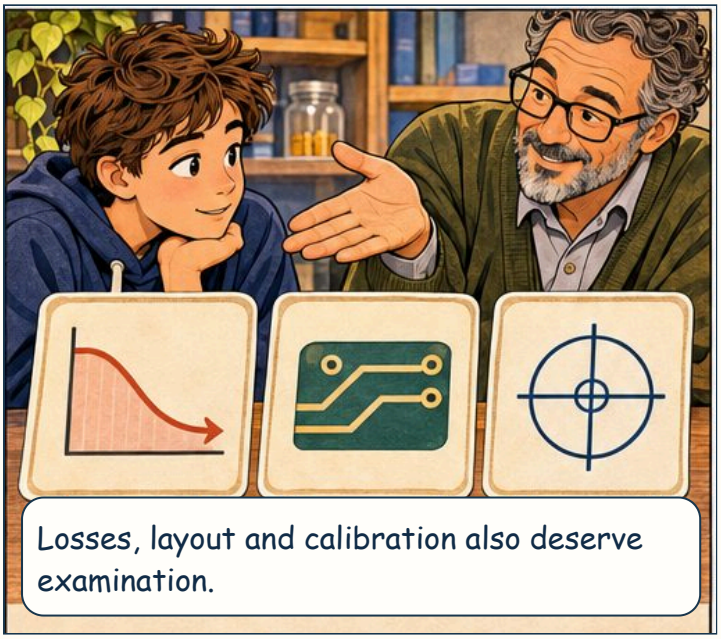
Understanding a difference



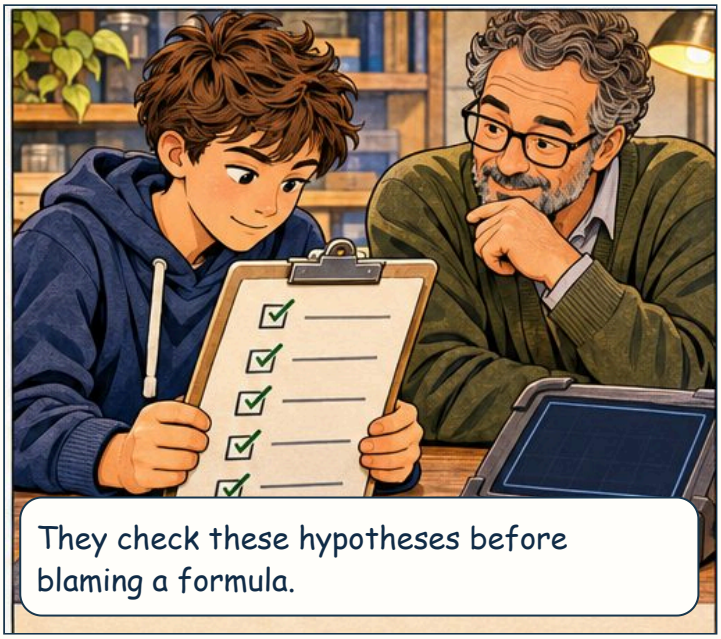
Observed cutoff may differ from calculated cutoff.



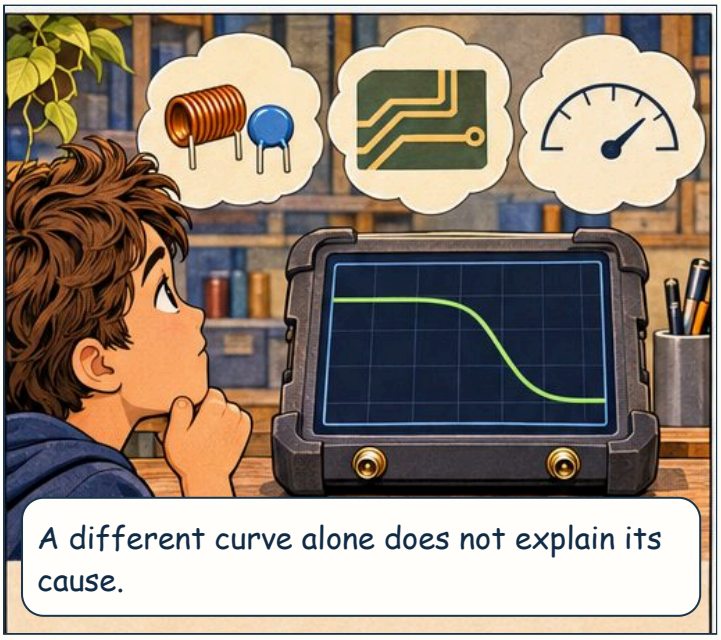
Selected values and their tolerances provide initial clues.



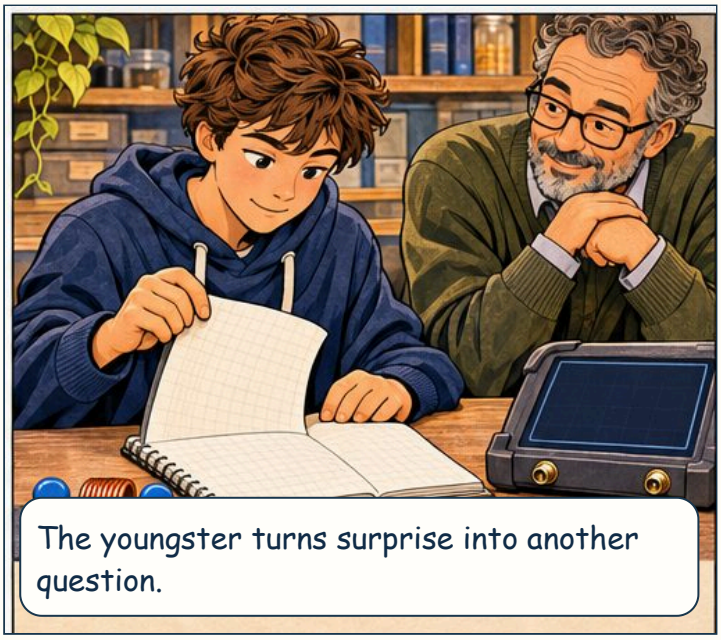
Losses, layout and calibration also deserve examination.



They check these hypotheses before blaming a formula.

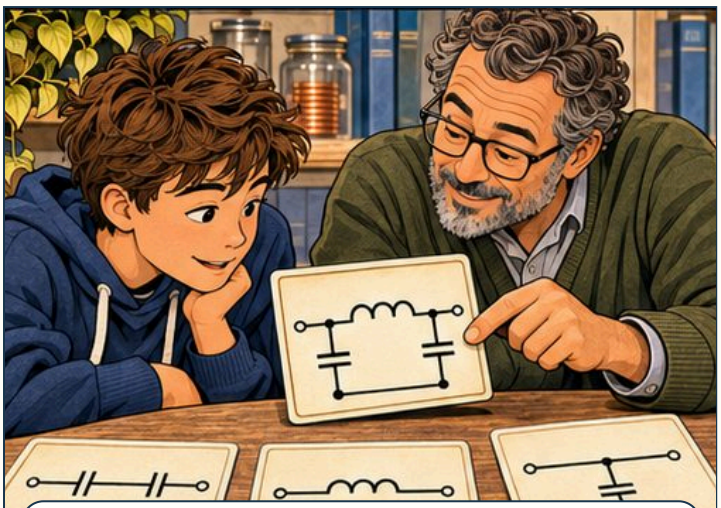


A different curve alone does not explain its cause.

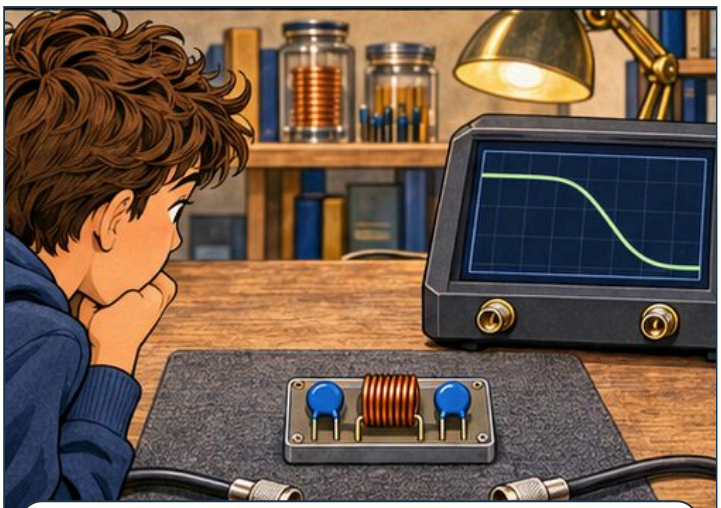


The youngster turns surprise into another question.

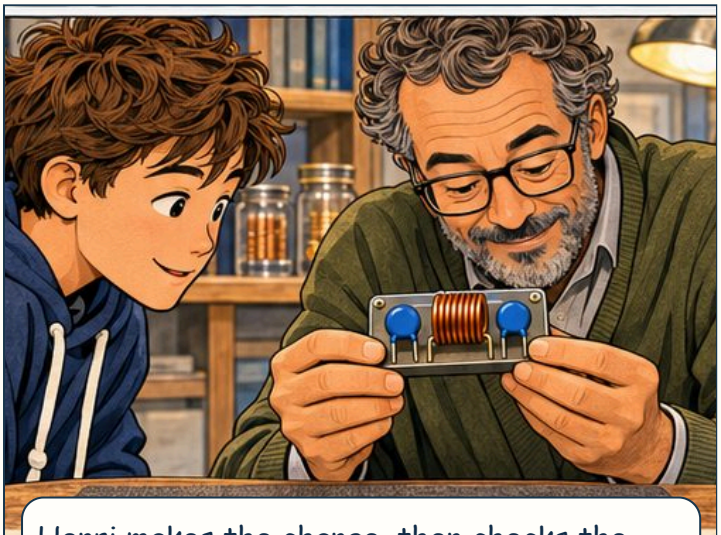
One change at a time



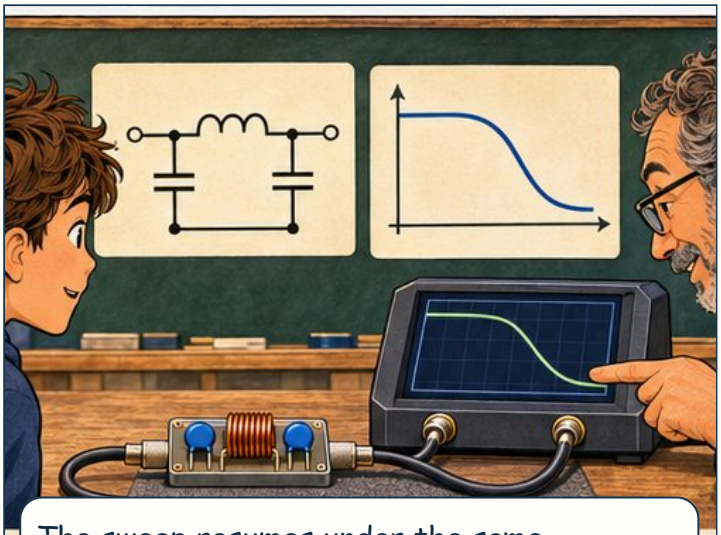
They select one hypothesis and plan a justified change.



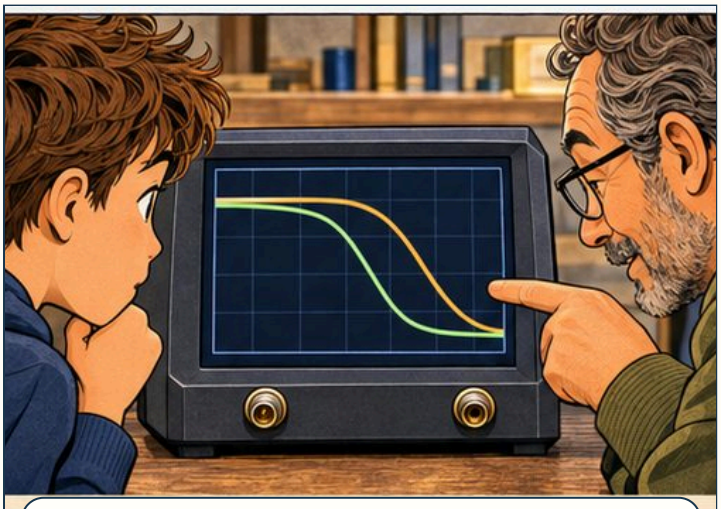
The source is stopped and the module disconnected before intervention.



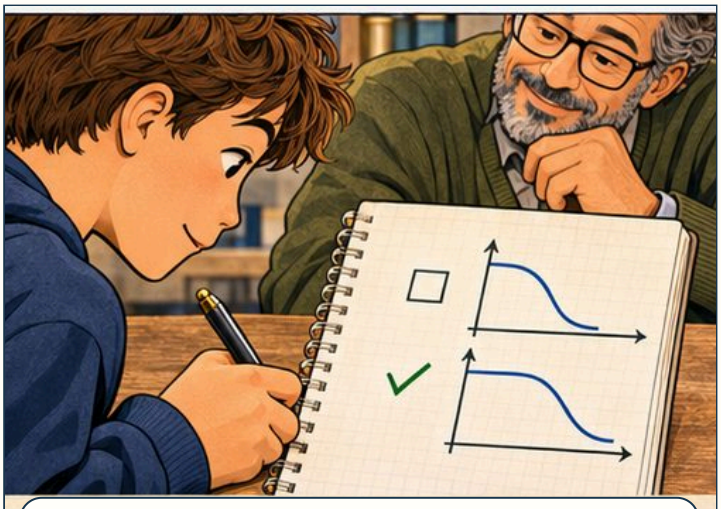
Henri makes the change, then checks the circuit.



The sweep resumes under the same documented conditions.

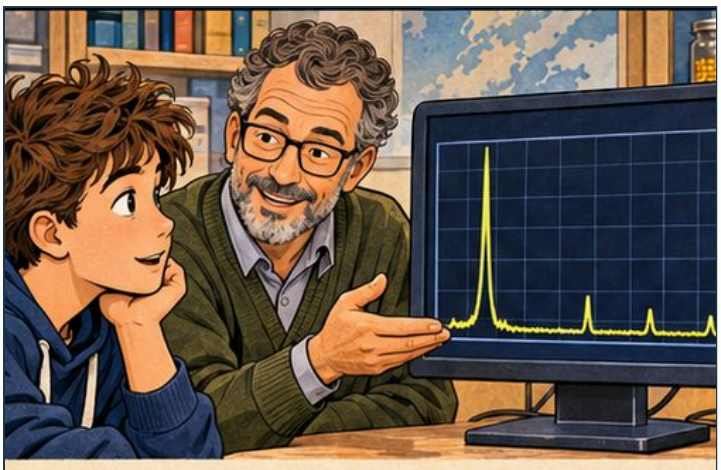


They compare the old trace with the new one.

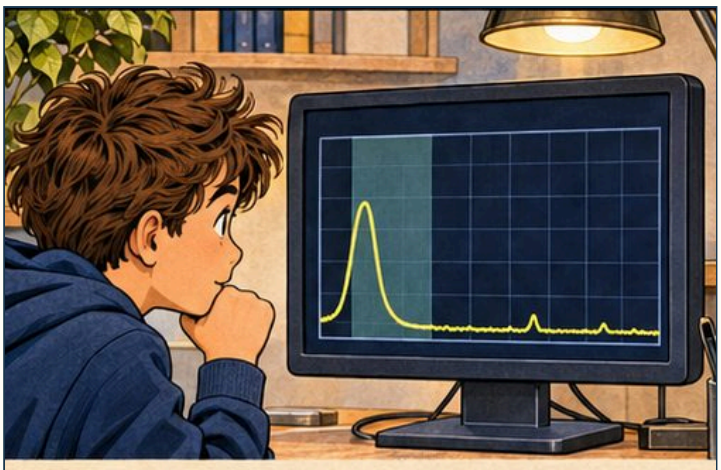


This method avoids mixing several possible causes.

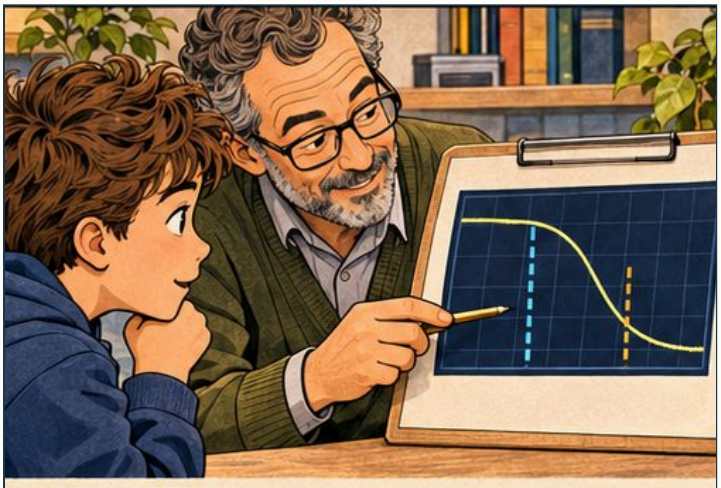
Attenuation has limits



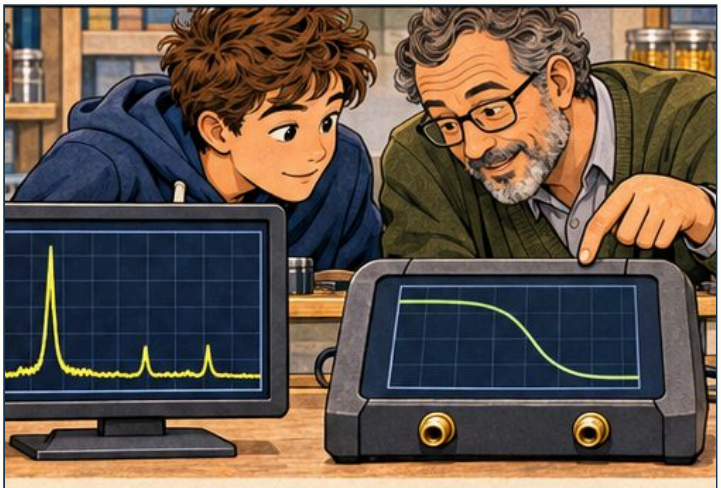
A low-pass filter does not erase every unwanted component.



A component inside its passband receives little attenuation.



Rejection depends on frequency and construction.



A full spectral check would require suitable additional measurements.

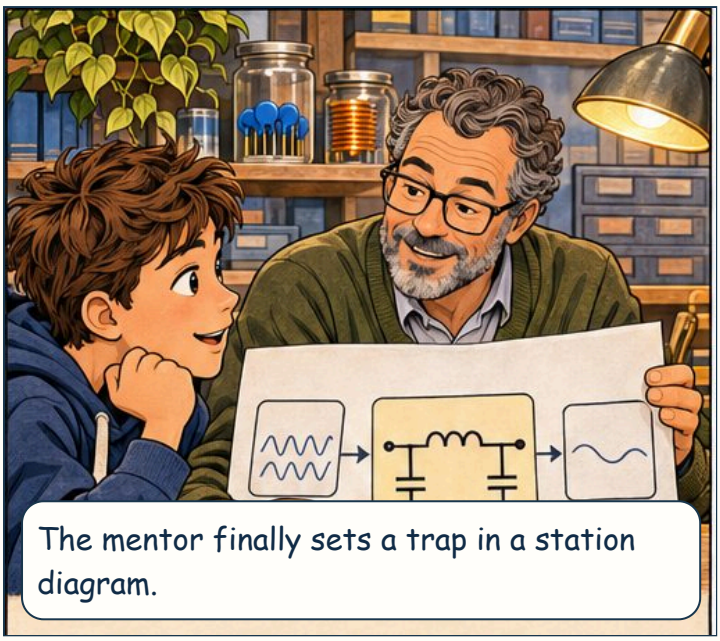


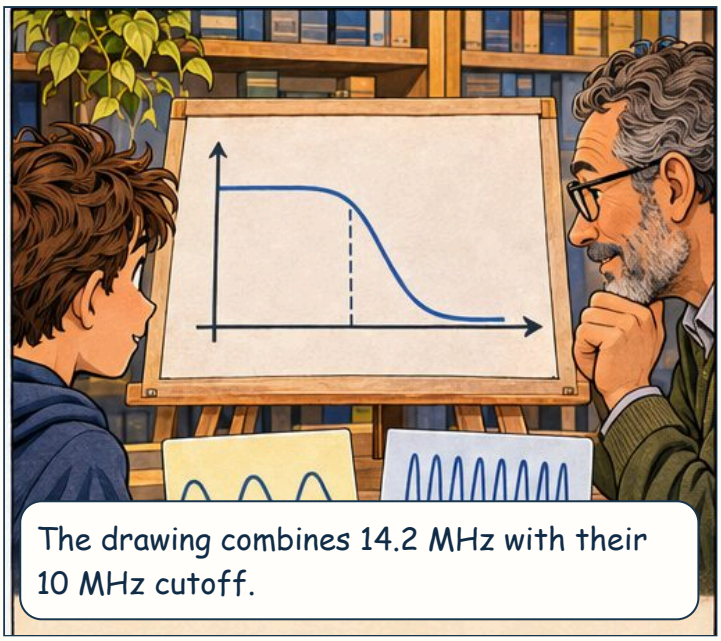
A filter's presence does not prove a station's compliance.

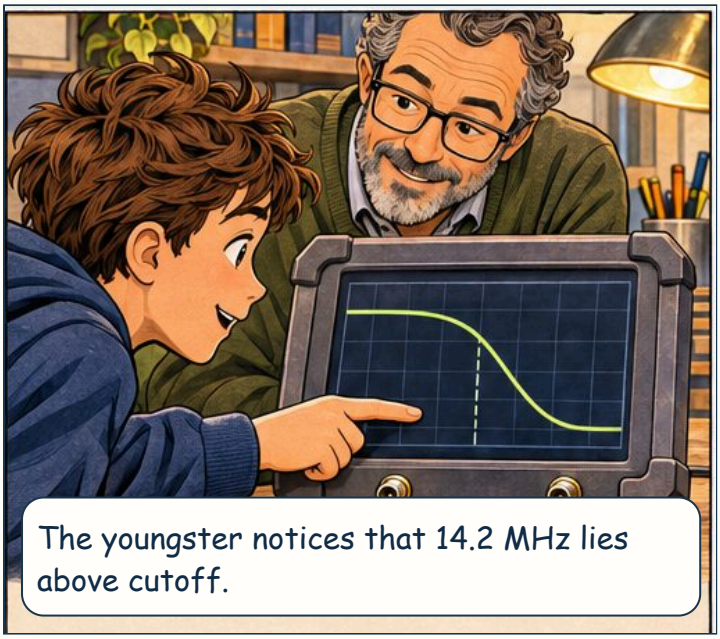


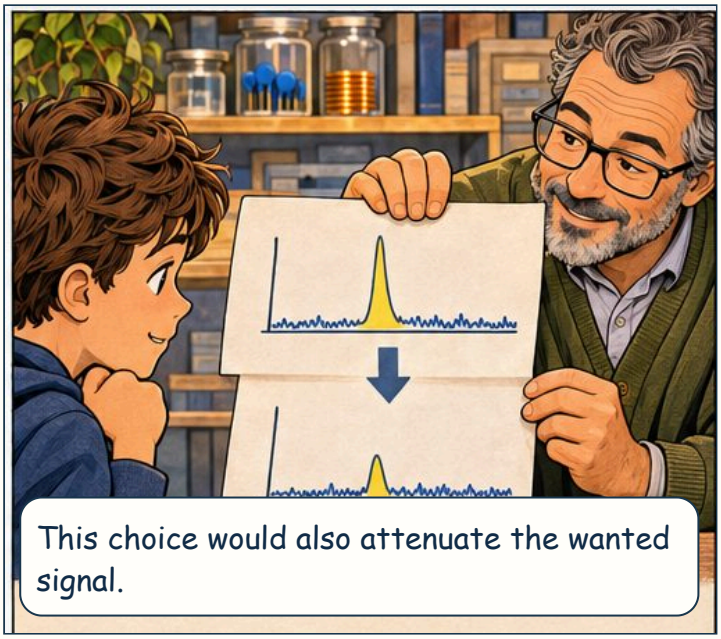
The youngster distinguishes a useful function from a general guarantee.

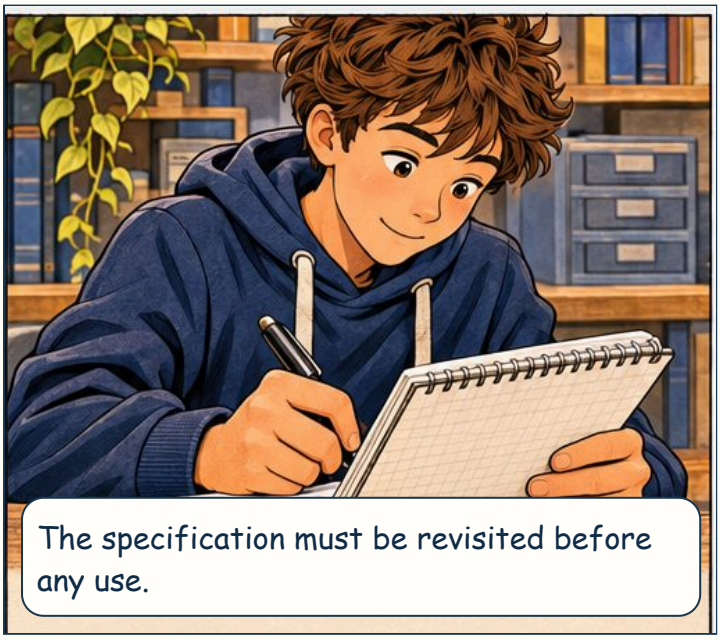
The wanted frequency must pass

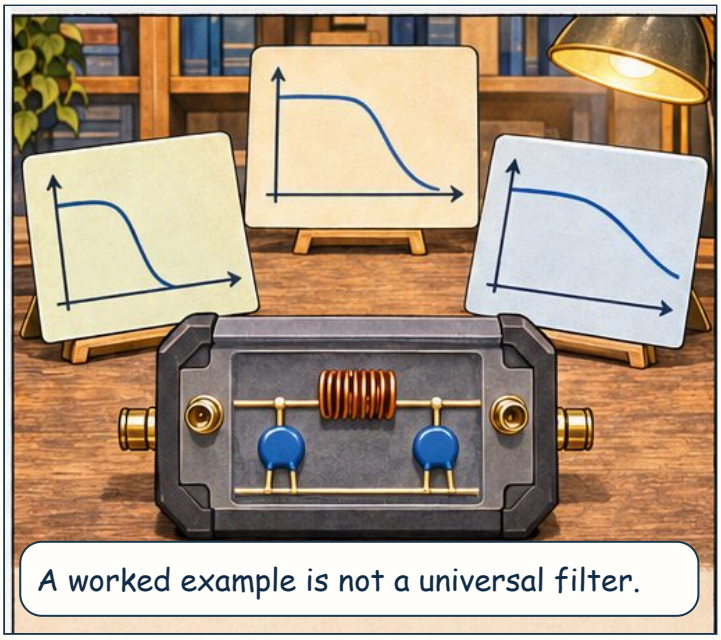




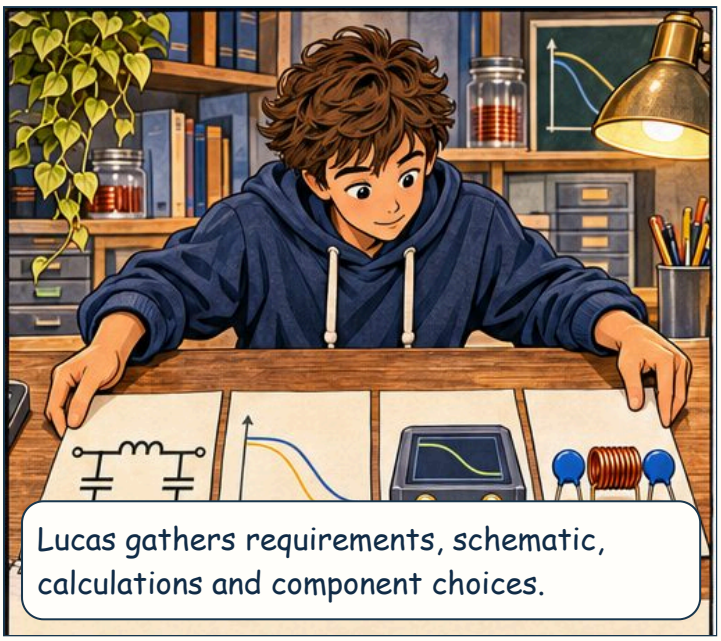




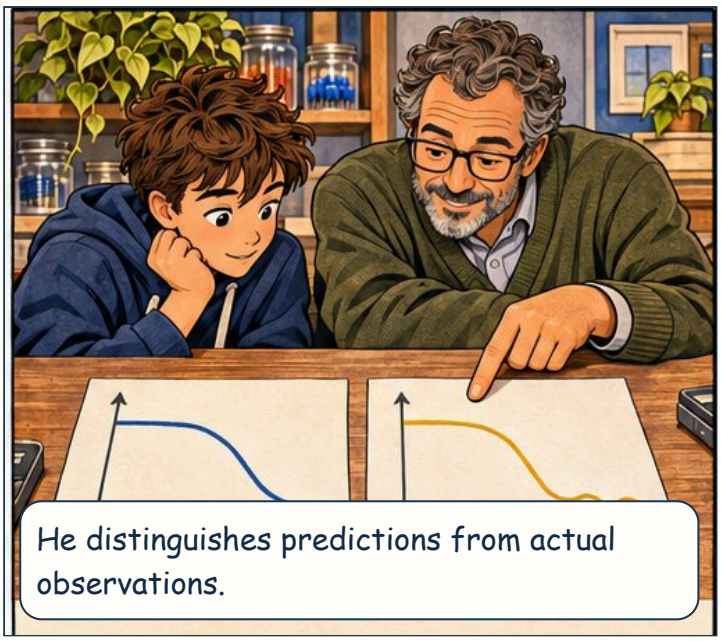




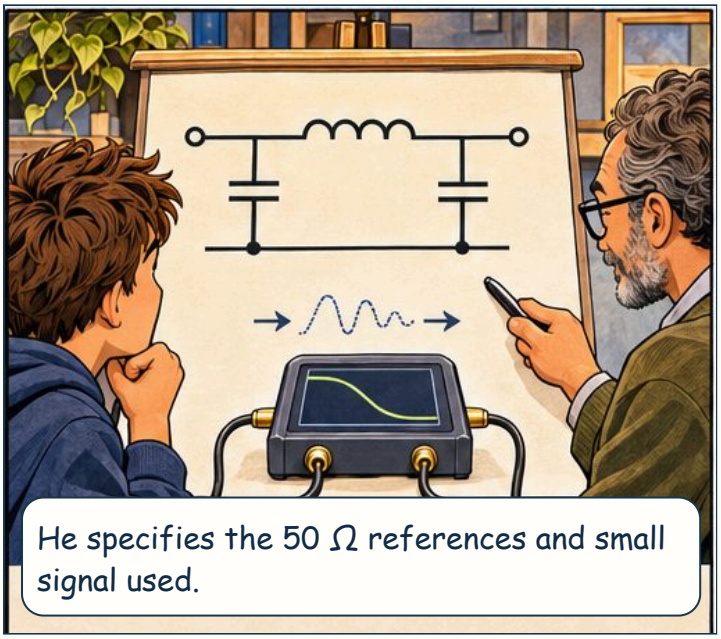
Preparing an explanation to share



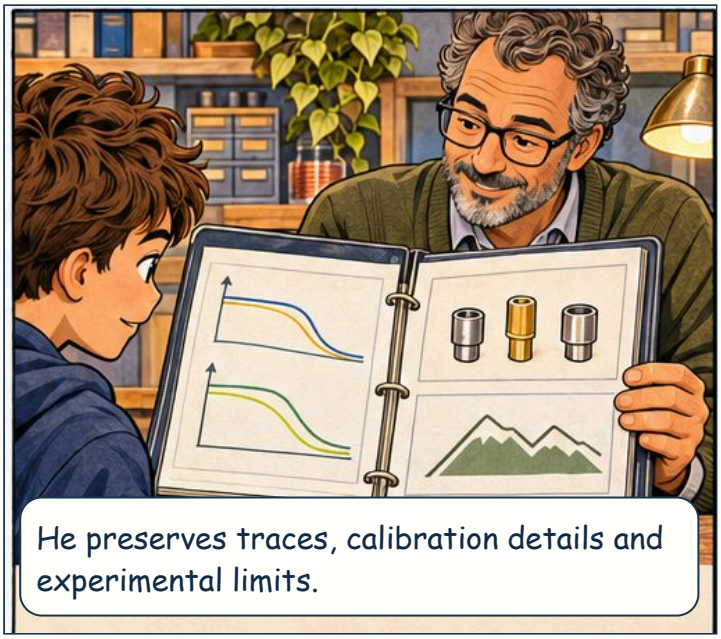
Lucas gathers requirements, schematic, calculations and component choices.



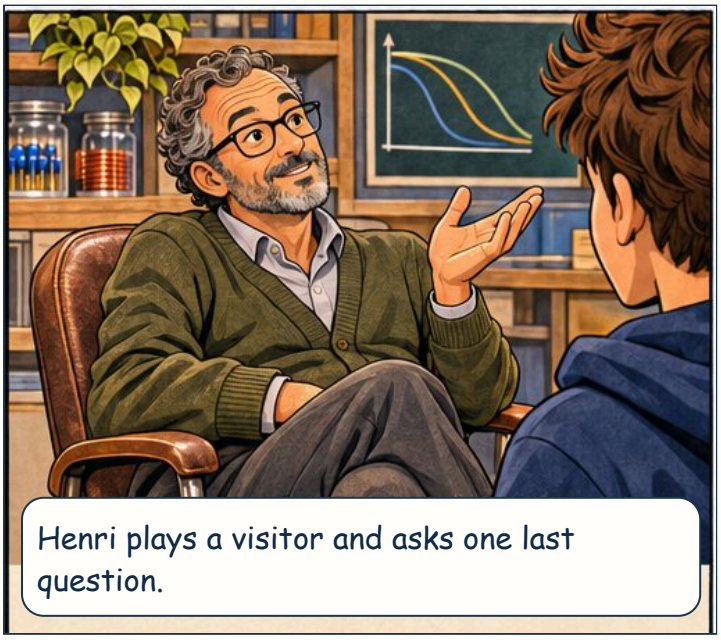
He distinguishes predictions from actual observations.



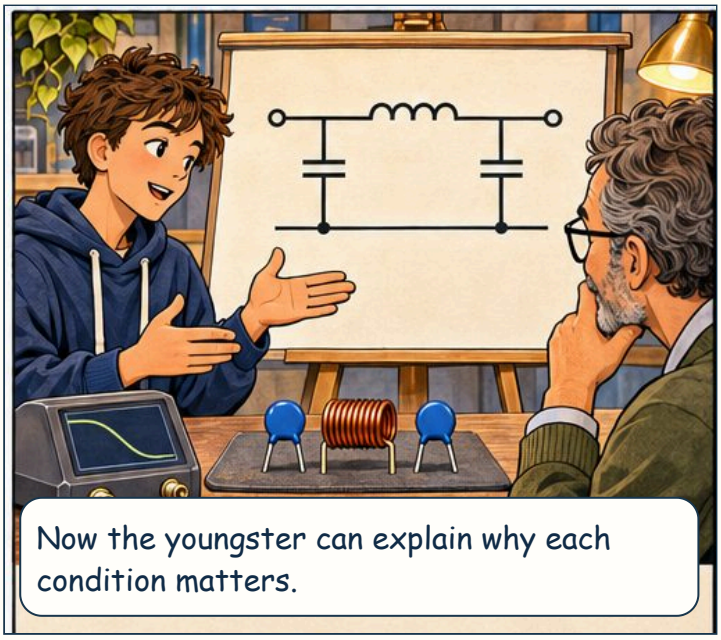
He specifies the 50 Ω references and small signal used.



He preserves traces, calibration details and experimental limits.



Henri plays a visitor and asks one last question.



Now the youngster can explain why each condition matters.

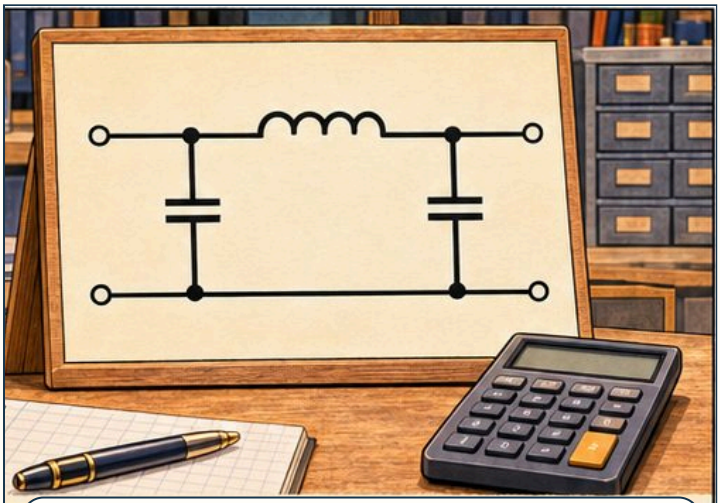
Understand, calculate, measure



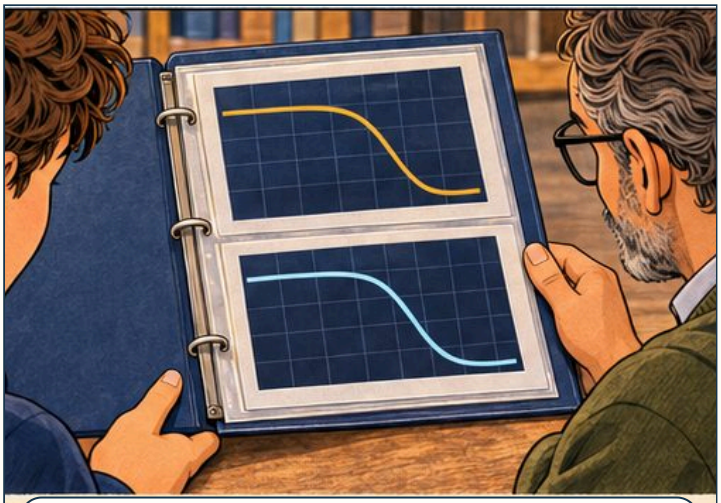
The three components return to their teaching box.



The youngster can now link a need to a filter response.



He can calculate this π Butterworth and check its units.



He can also measure, compare and investigate differences.



His notebook preserves a method, its assumptions and its limits.



At the club, the next discovery already begins with a question.