Electric & Magnetic Coupling Effects on Lines

A simulation survey by Dieter Stotz using Quickfield©

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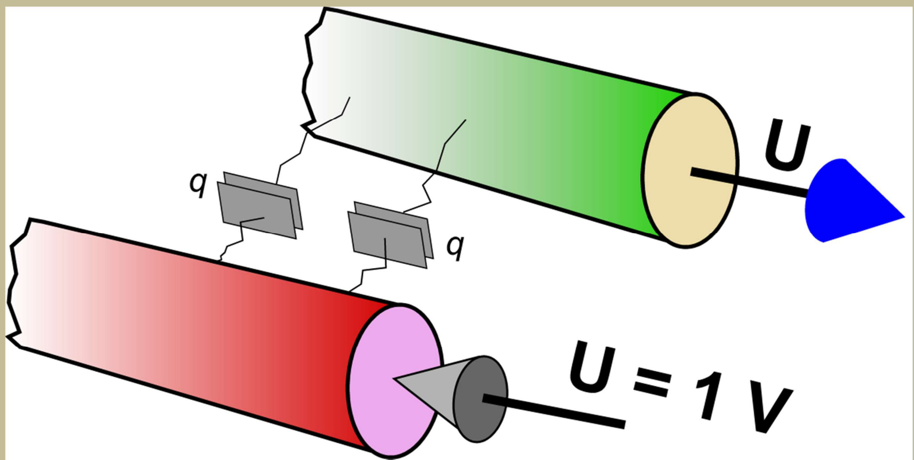
In this webinar we want to have a look at the influences between single lines in circuits or traces in PCBs. We will examine all important parameters like size, distance, shape and geometrical arrangement of conductive lines and traces.

General	AC Conduction	AC Magnetic

Very often it is the case that sensitive lines must not be shielded by ground, because then a line would be capacitively loaded. This can be undesired when the line is of higher impedance. Especially digital signals can become distorted and slopes can become flat and low – imagine for instance just I^2C signals, where the high state is driven by a resistor and not by a push-pull driver. But also analog lines are affected, for instance sensors.

Different aspects are of interest, like coupling voltage, current, loads and impedances.



The first arrangement is a simple pair of lines, where the wires represent a certain conductor diameter and have a defined distance. We will vary these parameters, as well as the frequency and the load at the affected line. So, normally you have a sending line and a receiving line with a load on it.

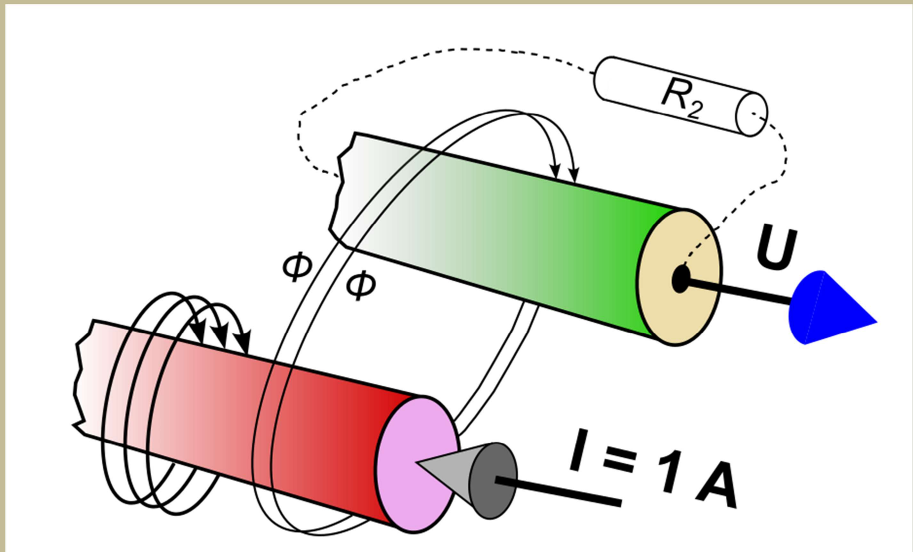
This first schematic figure illustrates two wires; the left wire (red) is connected to an AC voltage, and we want to examine the coupling by capacitive effects to the right wire (green).

Formally treated, the transferred charge quantity is in correlation to the capacity. This is shown in the equation, shown at the left side.

$$C = \frac{Q}{U} = \frac{Q}{1\ \mathrm{V}}$$

$$I = U \cdot \omega C = \omega \cdot Q$$

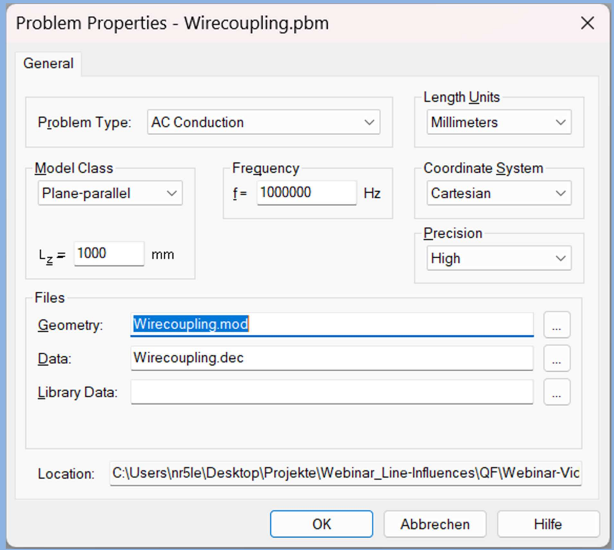
The capacity can be easily read directly from the charge value, as the voltage is set to 1 V. The current is valid for short circuit situation only and it is the charge multiplied with the angular frequency.



$$U = \omega \cdot \psi$$

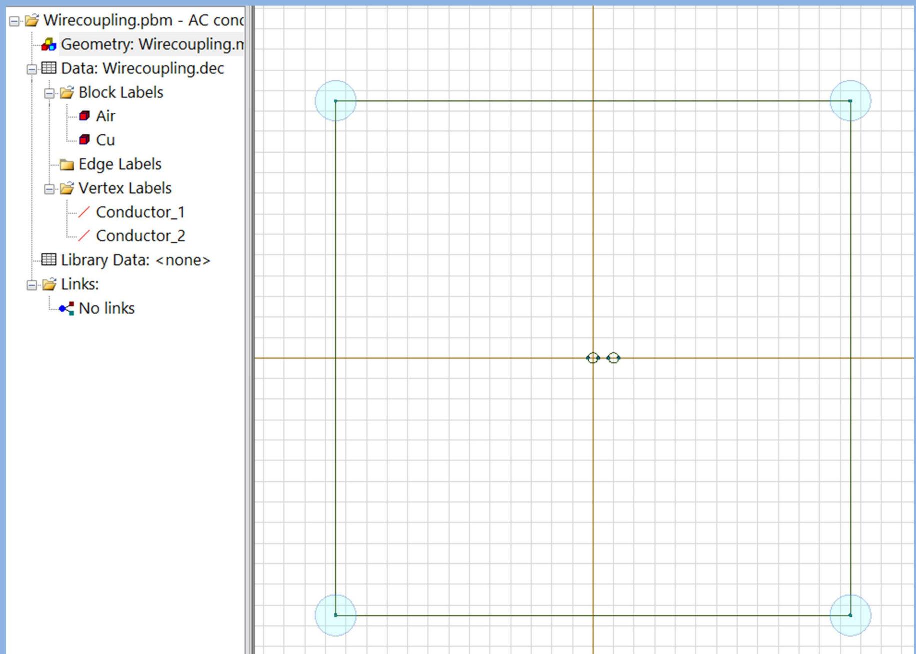
The second illustration is the link to the magnetic induction. The figure shows the two wires again, but this time the left wire is flooded by an AC current, which generates a magnetic alternating B-field. And this in turn induces a voltage to the right wire. A resistor in parallel to this line allows an induction current. The formulation is on the lower figure.
Please compare this with the upper equation. It is the product of magnetic flux with the angular frequency. The possible current inside the right wire depends on the resistive load and the impedance of the wire.

In general the two types of coupling from one conductor to a second one are appearing always together. To split the two coupling effects into separate examinations is a simplified possibility to get results, though.



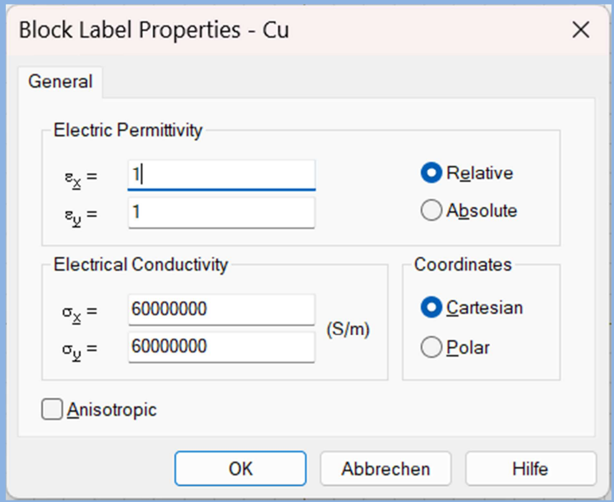
After the program's start and typing the name of your problem you must select the right type and class of the problem. As we want to examine AC voltages, you must take ***AC Conduction*** as the problem's type.

Length Units should be set to ***Millimeters*** and ***Model Class*** to ***Plane-parallel***, Axisymmetric is something rather for coils and other systems with cylindrical shapes.
For now, we set ***Frequency*** to 1 000 000 Hz (1 MHz).
The ***Precision*** is set to ***High*** and the length in z-direction is ***1000*** mm, so that every specific result can be scaled if using an individual length of wires.

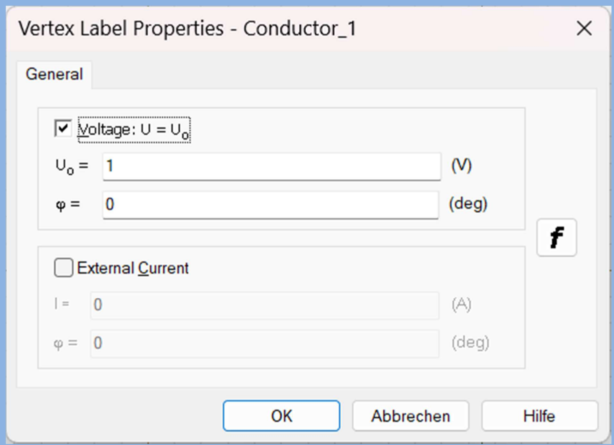


Next step is creating the components and their geometrical arrangement. We just need to create two wires as conductors. As we are looking at the profile, we should create a circle for a wire.
But first of all we do need to create an outer box as limitations of our examination volume. Don't make it too small, otherwise the results can become inaccurate. We can take a rectangle 50 x 50 at the position 0/0. It will be made by ***Edit/Insert Shape***.

Now, we can create two wires with a gauge of 1 mm each. It will be made again by ***Edit/Insert Shape***. Then we want to place them: The first in the center (0/0) and the second one in x-distance of 2 mm (2/0). This way, there will be a distance of 1 mm between the wires' surface.
You can create the second wire by duplicate and move of the first one (like it is shown) or you can place it by ***Insert Shape*** again like before.

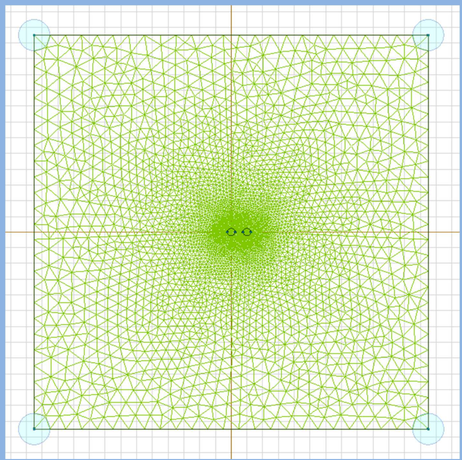


The next step is to define materials and parts' properties. This means the two wires must get material names, like *Cu* for copper (see last slide). In the problem window at the left side a part occurs with the name *Cu*, but still with a question mark. Both wires should use the same material. The whole space in the box also must get a material name and definition. It makes sense to name it Air.



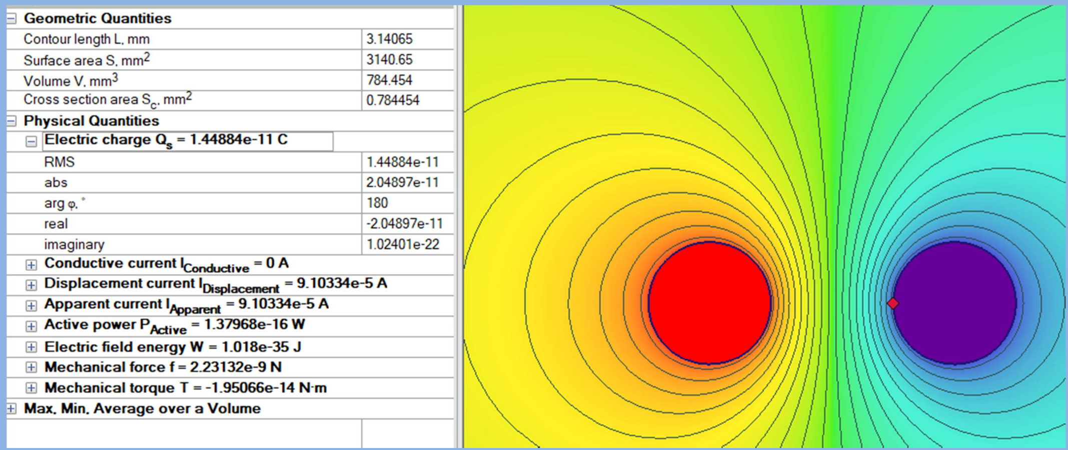
To determine the wires' voltages, we must create *Vertex labels*. For this we can name the vertexes of the center wire by *Conductor_1* and the other one *Conductor_2*. It is relatively irrelevant which one of the vertexes is selected, because the wire's high conductance distributes the same potential all over it, as long as there are very small currents.
To force the whole surface of the wires to be covered with the same potential, you also could use *Edge labels* instead of *Vertex labels*.

So we have some parameter names in the problem window, but they are still without values. We will do it now. ***Air*** **should be set to epsilon = 1 (*Electric Permittivity*) and *Electrical Conductivity* = 0. That's the ideal assumption.**
Copper (Cu) can be set to a very high epsilon value, and conductivity is approximately *60 million S/m*. Both values don't have critical influence to the results of our simulation, as long as both are quite high.
The voltage of the first wire is set to *1 V*, the other one to *0 V*. We will see later on, that this gives a good precondition to get very simply the capacity between the wires.



We are ready to solve the problem at the first time. The whole arrangement has to be divided by a mesh first, then you can start the solve command. The results are shown now, as soon as you click on the integral button and then you have to select the right wire by activating the contour of the wire.

It is recommended to refine the solution. This is done by solve and refine.



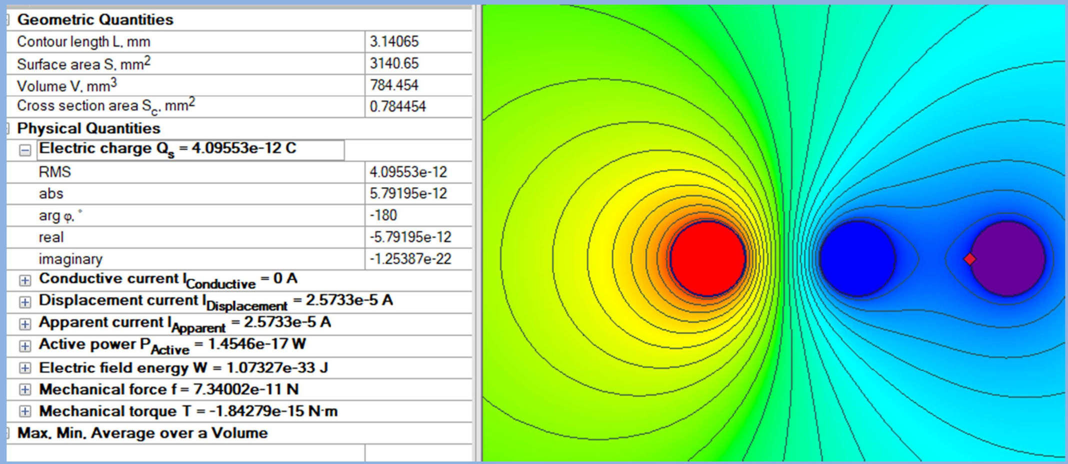
The finer resolution you can recognize at the rounded circles of the wires.
The result of the electric charge changed from about 11 pC (Pico-Coulomb) to about 14 pC by the higher resolution and precision.
But we are interested in the peak value, because this corresponds to the potential value of the left wire 1 V, which is also peak value.
What is the meaning of this? The interacting electrical charge between the two wires is developed by the voltage between the two wires.
The peak value of charge, divided by 1 V gives the capacity of the lines, based on the length of 1 Meter.
Quickfield shows the picture of the electric field with the E-vectors.

$$C' = \frac{\varepsilon \cdot \pi}{arcosh\,\frac{D}{d}} = \frac{8.854 \cdot 10^{-12} \cdot \pi}{arcosh\,\frac{4}{1}}\,\mathrm{F/m} = 13.48\ \mathrm{pF/m}$$

We are going to double the distance of the two wires now. This is made by selecting and moving the second wire to the right. The amount of movement is 2 mm.
Let's test the results again. As you can see, the charge value is decreasing as expected. Thus also the capacity is reduced by the same percentage.
You can save the new model geometry under a new name and allocate this with the problem.

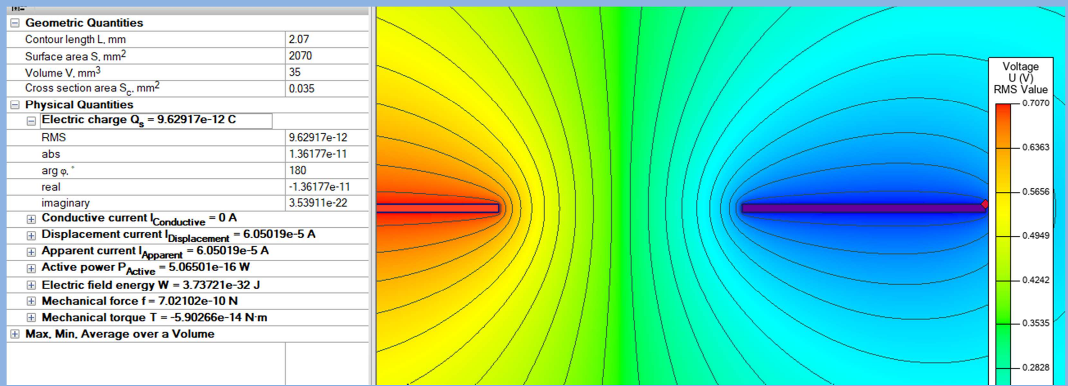
If you want to compare the simulation result of capacity, you can use the formula of the capacity of unit length as shown on the left.

As the length of the arrangement is 1 m, it is 13.48 pF. The simulation's value is 13.04 pF, which is about 3 % lower – a quite a good match.



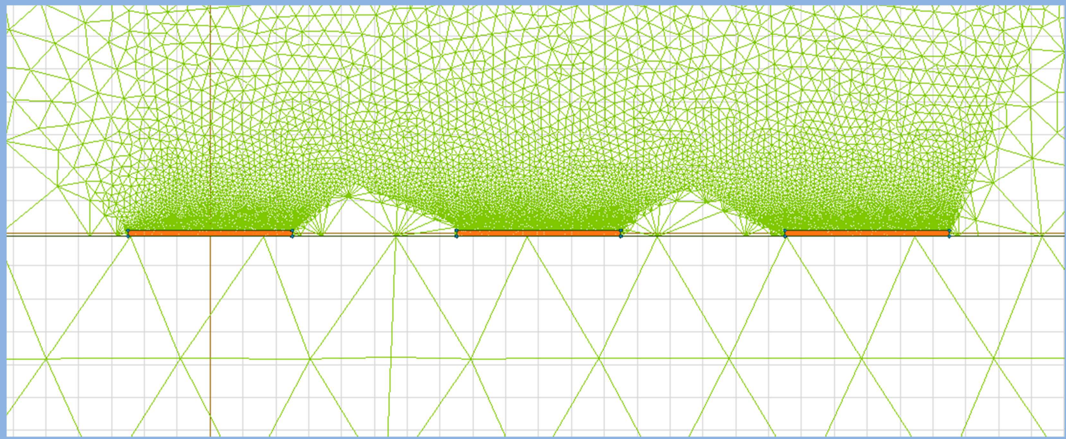
What will happen, if there was a third wire in the center of the both? It is like using a ribbon cable, where the middle wire is connected to GND. Remember, the vertex of wire 2 is set to 0 V, so after duplicating the vertex of the center wire is also connected to 0 V. Of course, you could give a new name to this vertex too and then set this vertex to 0 V.

Here are the results again. The capacity decreases to about 5.8 pF, much less than before. The middle wire says about 16 pF against it.



After the wire arrangements we will investigate the behavior of traces on a PCB. The wires in the model will be erased and the traces of the same width and distance will be created. These traces are just blocks and must be designated exactly, the vertexes too. Finally we have the analog state as before with wires.

The problem can be solved now, but it is a good idea to refine it once. Like before the values of electric charge and displacement current are the most interesting ones. Let’s write down the values.

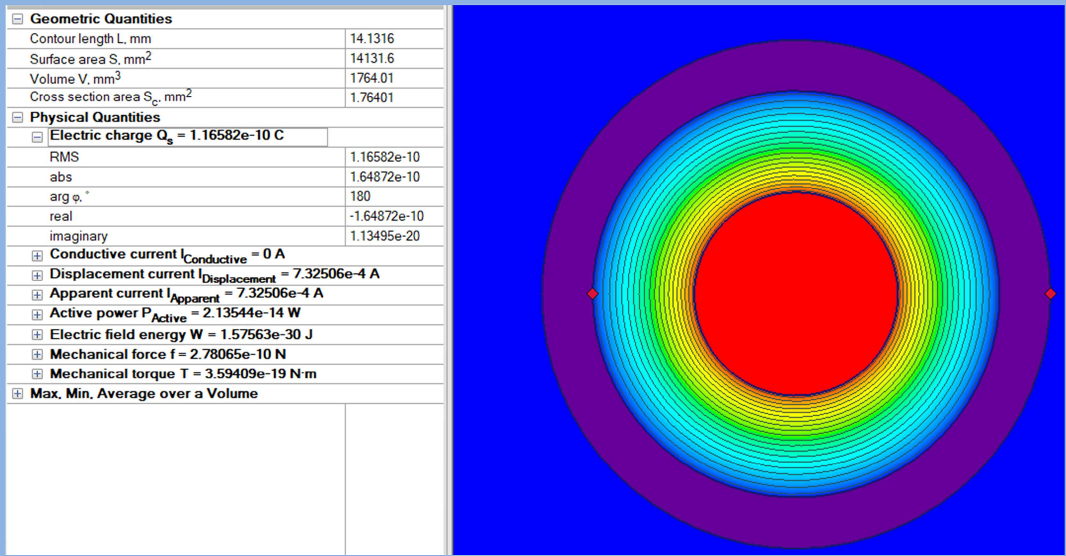


Increasing the distance to the double and fetching data is the next step.

In the center of the two traces we place a third trace. This must represent the same properties as the right trace, in particular ground or zero Volt connected. Thus it operates as a shielding barrier.

Further examination is adding a PCB and a vertex with GND potential. Consider that the PCB has some relative electric permittivity, value about 4.

The rightest trace has to be probed and the center trace too.



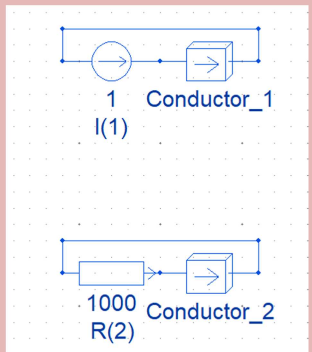
For the sake of completeness let's have a look at a common shielded wire under aspects of voltage potential. The second conductor is the screen, that is connected to ground. The charge transfer from the inside wire is a measure for capacity and thus the load is just reactive.
We create this from the two wires' simulation: Just erase the second wire and make two more concentric circles. The second ring is the isolation with some epsilon, and the outer ring is the grounded screen.

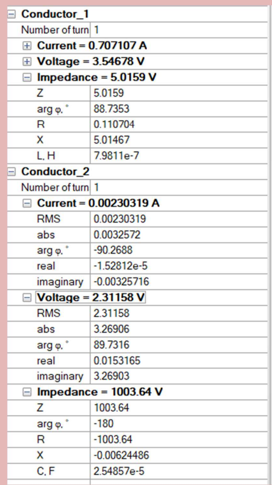
The inner conductor is connected to 1 V, while the screen outside is 0 V. Hence the ring of screen is dark blue and outside too anyways. That means screen saves the space outside from any voltage. And the inner conductor doesn't get any influence from outside either. But these extreme properties come at a cost of high capacity. The value can be read off from the charge. It is about 160 pF per one meter. This can be approved by Electrostatic and capacity wizard too. Please also compare the both values of the two conductors – they are almost the same, because there is nothing which can be lost. This can be approved by Electrostatic and capacity wizard too.

We step to a different effect of coupling, it is the electromagnetic induction by a current-carrying conductor. The voltage on a second conductor parallel and nearby the first conductor depends on many parameters like distance, frequency, length etc.

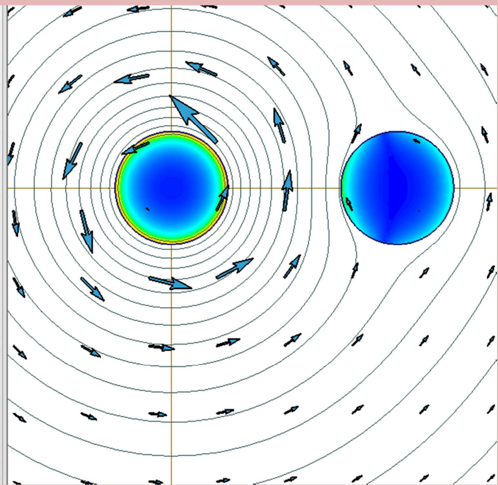
The old Two_wires model can be used, but there are some modifications necessary:

1. Change type to *AC Magnetics*
2. Boundary definitions necessary
3. Remove vertex labels. (We remove the vertex labels and use individual block names instead. This is why the blocks will be integrated in a special circuitry, which overtakes the electrical source and sink functions.)
4. New definition of block labels, like mentioned, and setting their parameters.



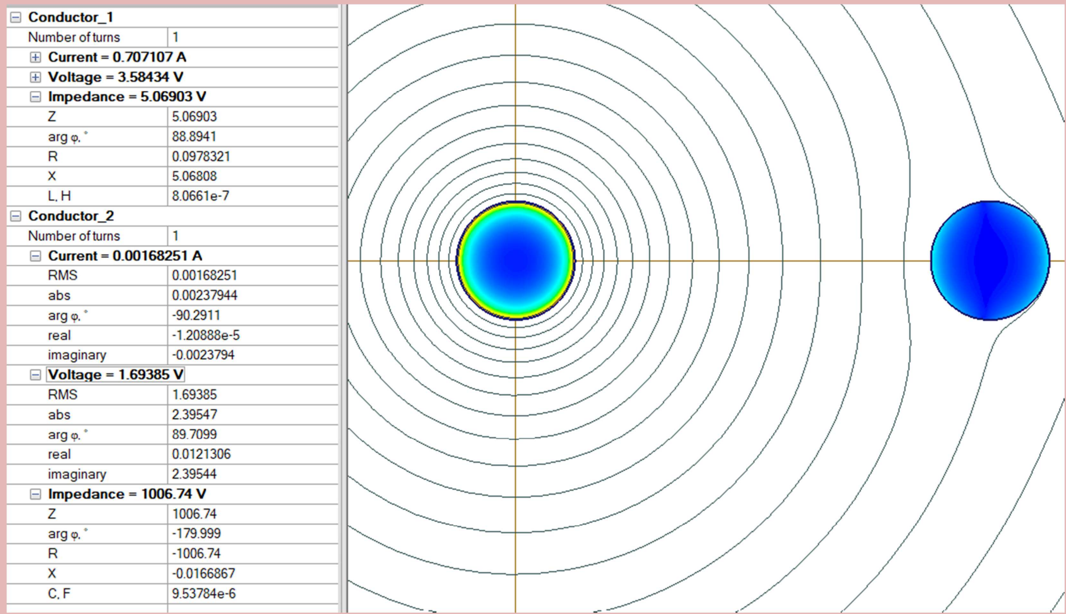


Conductor_1	
Number of turn	1
Current = 0.707107 A	
Voltage = 3.54678 V	
Impedance = 5.0159 V	
Z	5.0159
arg φ, °	88.7353
R	0.110704
X	5.01467
L, H	7.9811e-7
Conductor_2	
Number of turn	1
Current = 0.00230319 A	
RMS	0.00230319
abs	0.0032572
arg φ, °	-90.2688
real	-1.52812e-5
imaginary	-0.00325716
Voltage = 2.31158 V	
RMS	2.31158
abs	3.26906
arg φ, °	89.7316
real	0.0153165
imaginary	3.26903
Impedance = 1003.64 V	
Z	1003.64
arg φ, °	-180
R	-1003.64
X	-0.00624486
C, F	2.54857e-5

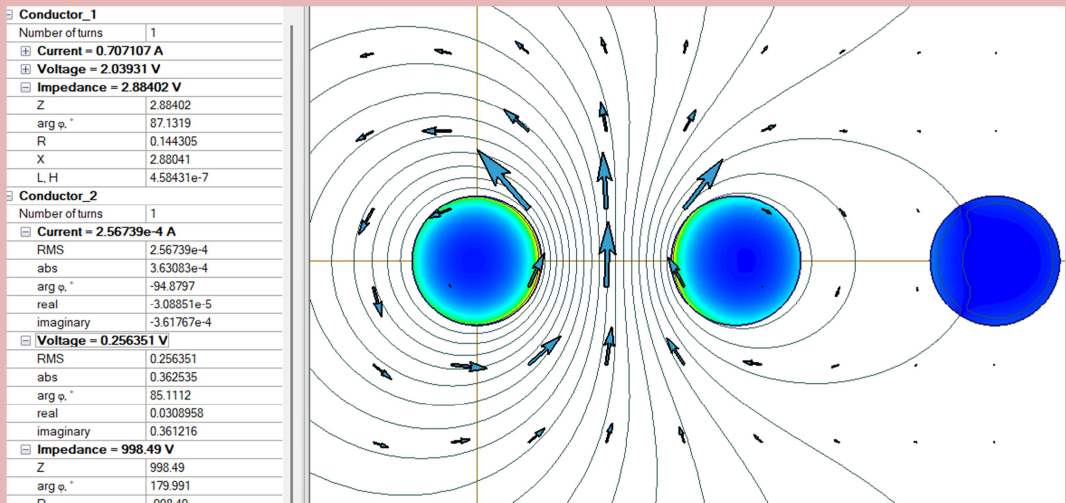


We click on *problem*, give a name for a circuit. Building the circuit: Current through one wire, resistor load on the second wire.

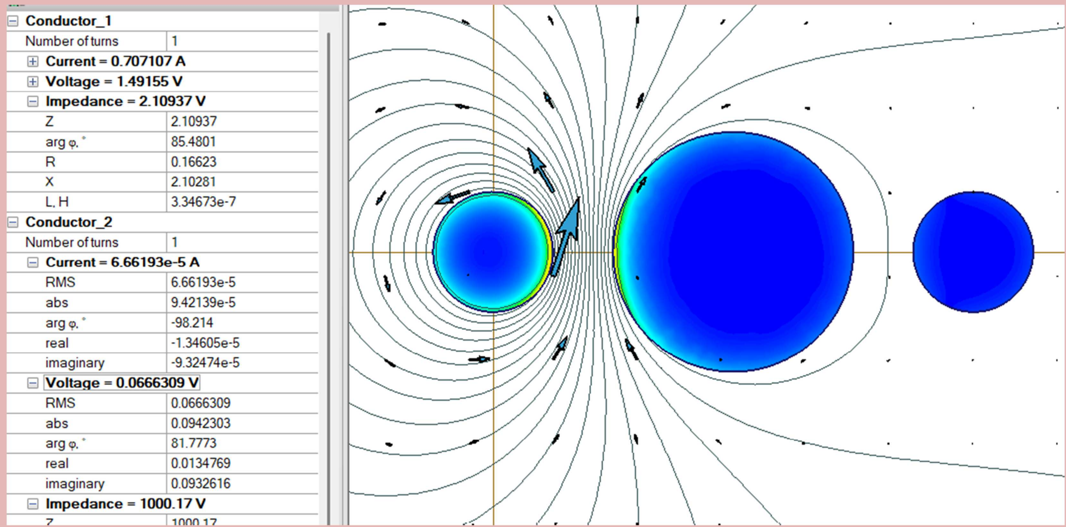
It is a similar situation like before for voltage coupling, but now it will be an induction effect, caused by the magnetic field of the left wire. In the field picture you can see the *current density*, represented by the color transition. And the skin effect is very conspicuous.
Quickfield shows the picture of the magnetic field vectors.



The same story, but in weakened state: We make the distance twice as much as before. The 'receiving' wire shows smaller skin effect now.

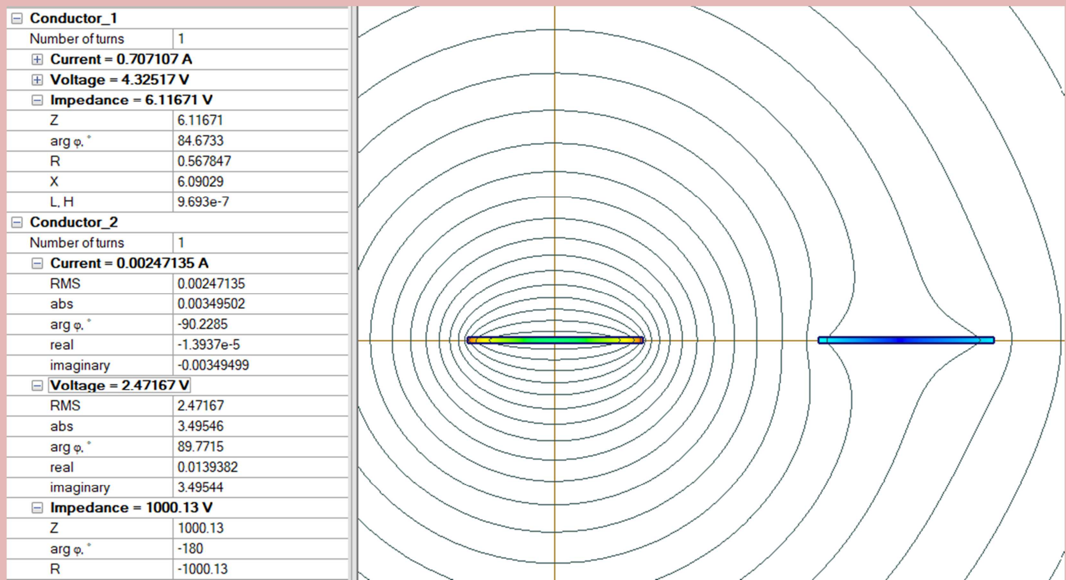


Next one is with three wires, where the center wire acts as ground screen. In the circuit this wire is shorted. You can solve that as it was done before.

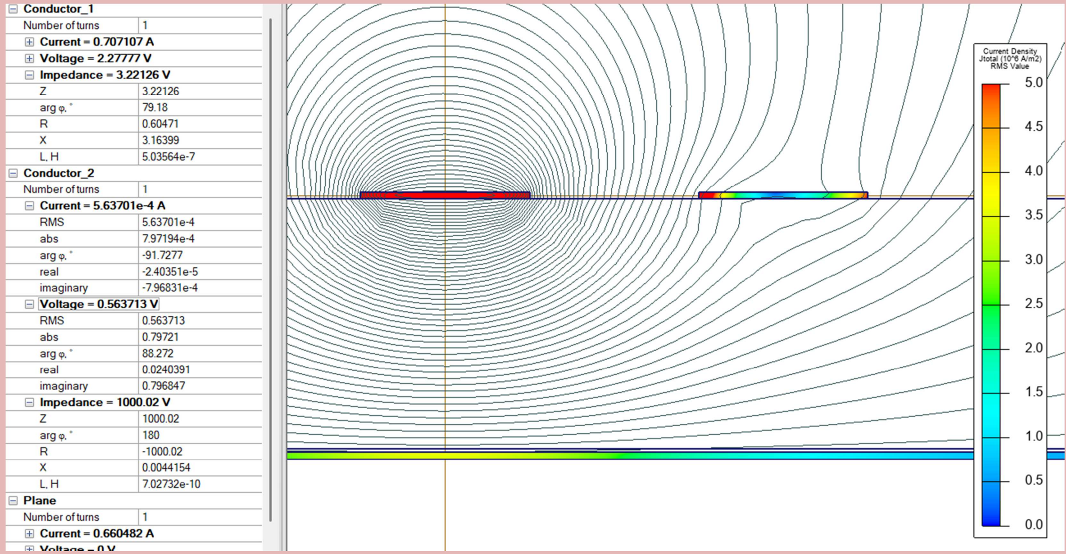


This screen wire will be increased by size, exactly it is of a double diameter now. Please look at the current in the right wire now. It is less than before, namely about the fourth. The same is with the magnetic flux.

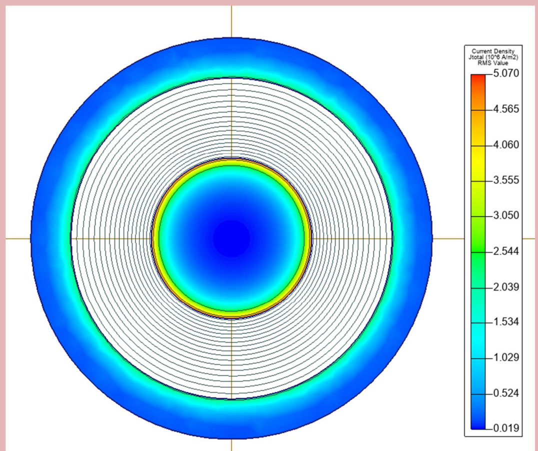
Here is the analysis of this very uncommon composition of different wires.

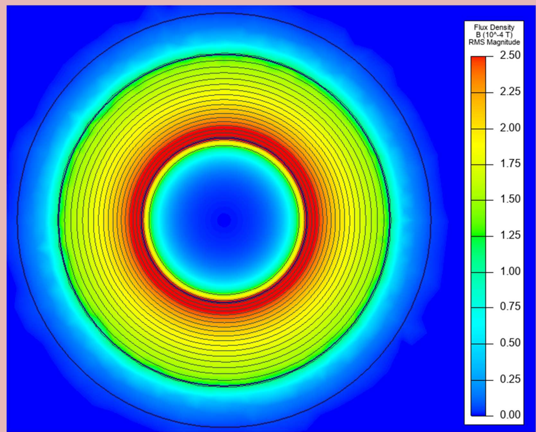


We game out the situations for two traces on a PCB. First one is with just two flat traces.



This one is a very common arrangement with two traces side by side and a ground plane on the other side of the PCB. Consider that the PCB has a permeability of nearly 1, like air.
You can increase the traces' distance and look, how the shielding effect increases too, that is the ratio of the currents through the second trace with and without the plane. (Simply change the block plane to air conditions.)





Remember the shielded wire before. This is the method of *AC Magnetics*. An AC current flows through the inner conductor, and in the screen that current flows back – this is the common use of a shielded wire. You can see the skin effect inside and on the screen the proximity effect. The field picture with the B-field says that the screen avoids B-fields too in the outer space. You can show the course of the B-field strength along the line through the wire. Outside the screen the field strength goes abruptly back to almost zero.

General settings: U1 = 1 V, f = 1 MHz		
Model	**el. Charge / pCb**	**displ. Current / A**
Two_wires	20,49	1,287E-04
Two_wires_dist	13,04	8,193E-05
Two_wires_shield	5,792	3,639E-05
Two_wires_shieldx2	3,331	2,093E-05
Wire_shielded	116,6	1,036E-03
Two_traces	13,62	8,556E-05
Two_traces_dist	9,794	6,154E-05
Two_traces_shield	4,938	3,102E-05
Two_traces_plane	0,7368	4,629E-06

This is a final discussion and conclusion.
The table provides the values of the voltage coupling effect. It contains all the model types and the AC charges in Pico-Coulombs and displacement currents to the critical conductor.

General settings: I1 = 1 A										
Model	**Freq/kHz**	**R_2/Ω**	**U_1/V & Z_1/Ω**	**$φ_1$/°**	**I_2/A**	**U_2/V**	**Z_2/Ω**	**$φ_2$/°**	**ψ/Wb**	**Remarks**
Two_wires	1	10	2,191E-02	14,05	3,259E-04	3,259E-03	10	180	5,198E-07	
	1	1 000	2,190E-02	14,06	3,356E-06	3,266E-03	1 003		5,198E-07	
	1	100 000	2,190E-02	14,06	2,028E-08	3,266E-03	161 200		5,198E-07	
	1 000	10	4,691E+00	78,32	2,900E-01	2,900E+00	10		4,626E-07	
	1 000	1 000	5,016E+00	88,74	3,257E-03	3,269E+00	1 004		5,203E-07	
	1 000	100 000	5,016E+00	88,86	2,891E-05	3,269E+00	113 100		5,203E-07	
	10 000	100 000	4,945E+01	89,61	4,072E-04	3,270E+01	80 310		3,680E-07	
Two_wires_dist	1	10	2,190E-02	14,06	2,391E-04	2,391E-03	10	180	3,813E-07	
	1	1 000	2,190E-02	14,06	2,388E-06	2,396E-03	1 003		3,813E-07	
	1	100 000	2,190E-02	14,06	2,266E-08	2,396E-03	105 700		3,813E-07	
	1 000	10	4,872E+00	83,55	2,124E-01	2,124E+00	10		3,387E-07	
	1 000	1 000	5,069E+00	88,90	2,379E-03	2,395E+00	1 007		3,813E-07	
	1 000	100 000	5,069E+00	88,96	1,390E-05	2,396E+00	172 300		3,813E-07	
Two_wires_shield	1 000	1 000	2,884E+00	87,13	3,631E-04	3,625E-01	998,5	180	5,770E-08	
Two_wires_shieldx2	1 000	1 000	2,109E+00	85,48	9,421E-05	9,423E-02	1000		1,500E-08	2mm center wire
Two_traces	1	10	4,762E-01	0,74	3,333E-04	3,333E-03	10	180	5,557E-07	
	1	1 000	4,762E-01	0,74	3,489E-06	3,490E-03	1 000		5,556E-07	
	1	100 000	4,762E-01	0,74	3,459E-08	3,491E-03	100 900		5,557E-07	
	1 000	10	5,772	75,68	2,871E-01	2,871E+00	10		4,787E-07	
	1 000	1 000	6,116	84,67	3,495E-03	3,495E+00	1 000		5,565E-07	
	1 000	100 000	6,116	84,78	3,520E-05	3,497E+00	99 360		5,566E-07	
Two_traces_plane	1	10	4,77E-01	0,44	1,547E-04	1,547E-03	10	180	2,580E-07	
	1	1 000	4,77E-01	0,44	1,620E-06	1,620E-03	1 000		2,580E-07	
	1	100 000	4,77E-01	0,44	1,629E-08	1,621E-03	100 600		2,580E-07	
	1 000	10	2,938	76,98	7,513E-02	7,513E-01	10		1,253E-07	
	1 000	1 000	2,938	78,16	8,179E-04	8,179E-01	1 000		1,302E-07	
	1 000	100 000	2,938	78,17	8,101E-06	8,184E-01	101 900		1,302E-07	

Next table represents data of all tested magnetic induction effects. Varied parameters were frequency and load on the second conductor. Indexes 1 correlate to the first conductor with the current of 1 A and Indexes 2 to the more or less open conductor 2.

Structure	Conductors	Capacitve/pF	Induction voltage @ 1 MHz	Capacitive relative	Induction relative
normal	wires	20,49	3,27	1	1
distance		13,04	2,40	0,636	0,733
shield		5,79	0,36	0,283	0,111
shield x2		3,33	0,09	0,163	0,029
normal	traces	13,62	3,50	1	1
plane		0,74	0,82	0,054	0,234

This is a very compact table of the most important trends.
While a simple duplication of the distance doesn't have much effect to the coupling, the insertion of a shortened wire does, especially with a thicker wire – see the blue fields of the table.
For the PCB we can state a good effect with the plane for the static voltage coupling only, but the induction effect is still very strong, as long as the traces' distance is not much bigger than the PCB's thickness.
Needless to say, that frequency has a strong influence to both types of coupling. Capacity admittance is increasing with frequency by $\omega \cdot C$, the same as the induction voltage by $\psi \cdot \omega$.