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Training for Signal Integrity and Interconnect Design

What Really Is Inductance?

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Introduction

There is not a single person involved with signal integrity and interconnect design who has not used the term inductance at one time or another. Yet, very few engineers use the term correctly. This is fundamentally due to the way we all learned about inductance in high school or college physics or electrical engineering.

Traditionally, we learned about inductance and how it related to flux lines in coils. Or we learned about integrals involving magnetic field densities. While all of these explanations may be perfectly true, it doesn't help us on a practical level. How many boards have you designed that have coils in them? We have not been trained to apply the concepts of inductance to the applications we face daily, related to interconnects in packages, connectors or boards. If you really want to understand what inductance is, at an intuitive level, and use it to help improve the performance of your products, forget what you've been taught in school, and read on.

Counting Field Lines

First, recognize that there is this fundamental entity, called magnetic field lines that surrounds every current. If you have a straight wire, colored red, for example, and send a current, like 1 Amp, through it, there will be concentric circular magnetic field lines created around the wire, as illustrated in figure 1. You can imagine walking along the red wire and counting the specific number of field lines that completely surround it.

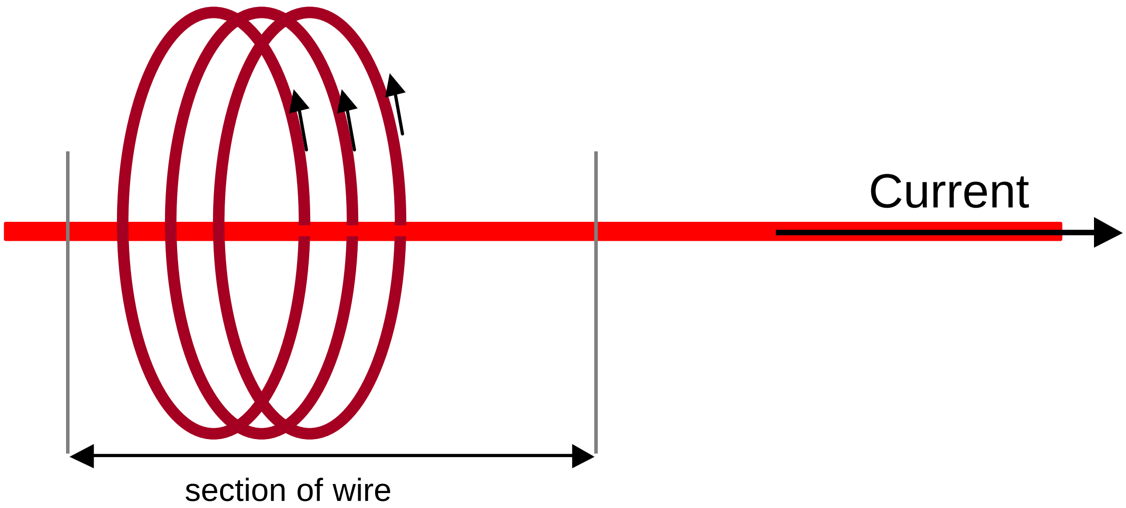

Figure 1 Surrounding a current carrying conductor are concentric circular magnetic field lines.

These field lines have a specific direction. To determine the direction, we use the familiar right hand rule. Point your thumb in the direction of the current and your fingers curl in the positive direction of the field lines.

In what units would you count the field lines? We count pens in units of gross. There are 144 pens in a gross. We count paper in units of reams. There are 500 pages in a ream. We count apples in units of bushels. How many apples are there in a bushel? I don't know, but I know there is some number of apples. Likewise, we count the number of magnetic field lines around a current carrying conductor in units of Webers. I don't know how many field lines are in a Weber, but there is some number. As you would predict, if you double the current in the red wire to 2A, you will double the number of Webers of magnetic field lines that are around it.

Inductance is fundamentally related to the number of magnetic field lines around the wire per amp of current in the wire. The units we use to measure inductance is Webers per Amp. One Weber/Amp is given the special unit, Henry. For most interconnect structures, when we describe their inductance, it is typically such a small fraction of a Henry, it is more common to use the units of a nano Henry. A nanoHenry, typically abbreviated as nH, is a measure of how many Webers of field lines we would count around a conductor per amp of current through it.

Why Inductance Plays Such An Important Role.

A second property of magnetic field lines is that when the number of field lines around a wire changes, for whatever reason, there will be a voltage created across it. The voltage created is directly related to how fast the number of field lines, N, change: $\Delta V = \Delta N/\Delta t$. Since inductance is related to the number of field lines around a wire per amp of current, the number of field lines is really $N = L \times I$. The voltage created, or induced, across a wire can be related to the inductance of the wire and how fast the current in it changes: $\Delta V = L\ \Delta I/\Delta t$. This is why inductance, in general, is something to be reduced, as it contributes to noise whenever the current changes, as when a signal switches.

Because the voltage induced depends on how fast the current changes, we sometimes call the noise created when the current switches through an inductance, switching noise or delta I noise, or ground bounce. Delta I noise across a conductor is completely unbiased about whose current created the field lines, whether it is the field lines from its own currents or another conductor's current. If we happened to have an adjacent current near the red wire, some of the field lines from this second wire may surround the red wire. If the current in the second wire changes, it will cause a voltage to be created across the red wire.

When it is another conductor in which the current changed, we usually call the induced noise in the adjacent conductor, cross talk. To be able to analyze real world problems that involve multiple conductors, we need to be able to keep track of all the various currents which are sources of field lines. The effects are the same, its just more complicated when there are many conductors, each with possible current and magnetic field lines. It is to describe the possible combinations of conductor pairs that the various flavors of inductance come in.

Self And Mutual Inductance

In addition to the red wire and its current and field lines in the above example, suppose there were to be another wire, a blue wire, with its own current, field lines and inductance. We bring it close to the red wire. When we count the field lines around the red wire, we will get a different number depending on the current in the blue wire. If the currents are in the same direction, bringing the blue wire close to the red wire will have us count a higher number of field lines around the red wire. But if we keep track of what currents created what field lines, we can keep straight the influence of each conductor. When we count field lines, we want to label the magnetic field lines that come from the wire's own currents, separate from the magnetic field lines that come from another wire's currents.

To distinguish the source of the field lines, we use the term self to refer to the field lines from its own currents and mutual to refer to the field lines around one wire, from another conductor's currents. With this new perspective, the self inductance of a wire is the number of field lines from its own current, per amp of current. This will be independent of the presence of another conductor's current.

If we bring a blue wire near the red wire, there will be a mutual inductance between them. This is the number of field lines that are around both wires, per amp of current in one of the wires.

Figure 2 illustrates the field lines that compose self and mutual inductance. We measure mutual inductance in nH as well, since it is also a number of field lines per amp of current. Obviously, as we pull the wires apart, the mutual inductance between them will decrease.

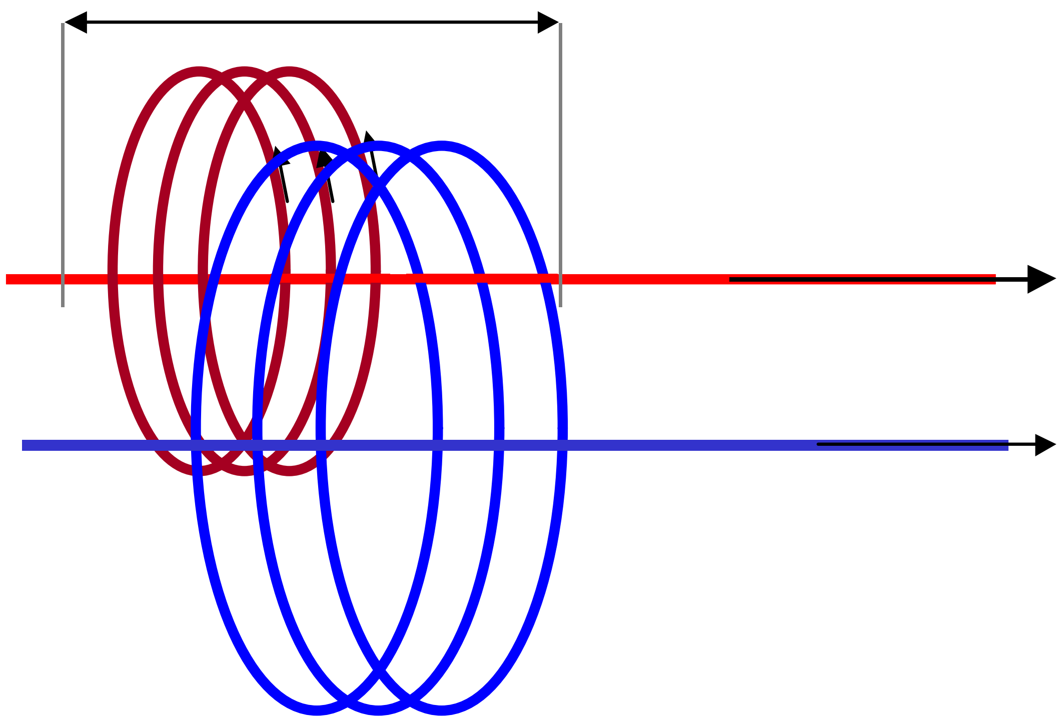

Figure 2 When a second wire carries a current, some of its field lines will completely surround the first wire. These magnetic field lines contribute to the mutual inductance between the conductors.

Partial Inductance

Of course, real currents flow in complete circuit loops. We have been looking at just a section of a wire. In this view, the only current that exists is the specific current in the section of wire we have drawn. When we have been counting field lines, we have ignored the field lines from the current in the rest of the circuit. This type of inductance is called the partial inductance of the wire, to distinguish the fact that we are looking at only a part of the loop. In reality, you can never have a partial current- you must always have current loops, but the concept of partial inductance is a very powerful tool to understand and calculate the other flavors of inductance, especially if you don't know what the rest of the loop looks like yet.

Partial inductance has two flavors; partial self and partial mutual inductance. What we have been discussing above has really been the partial inductance of the blue and red wires. More often than not, when referring to the inductance of a lead in a package, or a connector pin, or a surface trace, we are really referring to the partial self inductance of this lead. As a rough rule of thumb, the partial self inductance of a round wire is about 25 nH/inch of length. So, a wire bond 100 mils long, has a partial self inductance of about 2.5 nH. A surface trace from a capacitor to a via, 50 mils long, has a partial self inductance of about 1.2 nH. A via through a board, 064 mils thick, has a partial self inductance of about 1.4 nH. For better approximations for partial self inductance and partial mutual inductance, see reference 1.

In general, the mutual inductance between two wires is a small fraction of the self inductance of either one, and drops off very rapidly as the wires are pulled apart. For example, two wire bonds may each have a self inductance of 2.5 nH. If they are on a 5 mil pitch, they will have a mutual inductance of only 1 nH. This means that if there were 1A of current in one wire bond, there would be 1 nH x 1 Amp = 1 nanoWeber of field lines around the second wire bond.

As a rough rule of thumb, when the spacing is comparable to the length, the partial mutual inductance is down to 10% the self inductance. Two vias, 30 mils long, spaced on a 50 mil pitch, have virtually no mutual inductance between them and are completely independent.

Loop Inductance

Suppose the red wire loops back on itself, as in Figure 3. The current in one leg produces field lines around the other one, but in the opposite direction. We can count the field lines around the entire loop by starting the count with the top half and adding ***all*** the field lines that are around the bottom half.

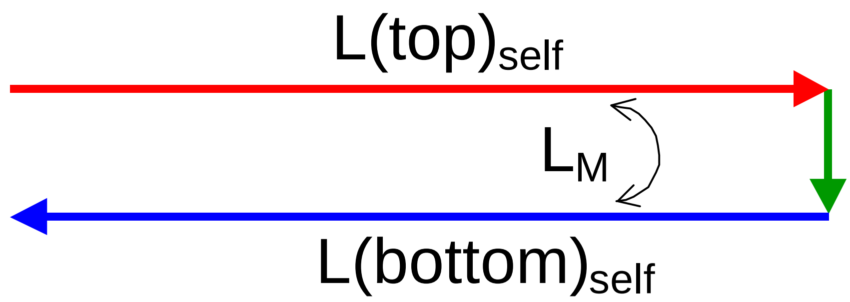

Figure 3. When both wire segments are part of the same loop, the current in the top segment is in the opposite direction as the current in the bottom segment. The field lines from the bottom segment, around the top segment will be in the opposite direction, and subtract from the field lines in the bottom segment.

The total number of magnetic field lines around the top half are first due to its own current and self inductance, $L(top)_{Self}$ x I, and the mutual inductance with the bottom half, L_m x I. However, the current is in the opposite direction on the bottom wire and thus, the field lines from the mutual inductance are in the opposite direction and subtract from the field lines from the self inductance. The total number of field lines around the top half of the loop is $(L(top)_{self} – L_m)$ x I.

Looking at the bottom wire, the field lines around it are due to its self inductance minus the mutual inductance, $(L(bottom)_{self} – L_m)$ x I The total number of field lines around the complete loop, per amp of current in the loop is thus $(L(top)_{self} + L(bottom)_{self} – 2\ L_m)$. If the two halves of the loop are identical, and their self inductances are equal then the total loop inductance is the familiar: $2L_{self} – 2\ L_m$. If we know the partial self and mutual inductance's of each section of the loop, or any collection of conductors, we can calculate the loop inductance of any path.

Loop Inductance in Transmission Lines

When we look at signals propagating in a transmission line, the current, at the wavefront, is flowing though a loop composed of the partial self inductance of the signal path, and the partial self inductance of the return path. This is illustrated in Figure 3.

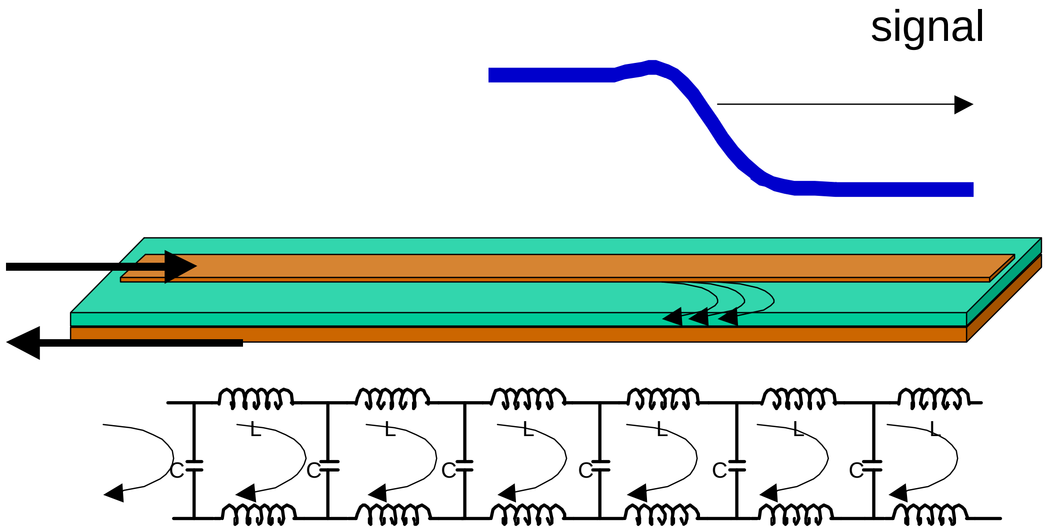

Figure 4 The current at the leading edge of a signal is propagating in a loop that includes the signal path and the return path immediately beneath it.

When the transmission line is "balanced", as for example, twisted pair, or some types of coplanar lines, the partial self inductance of the two paths are equal. When the line is asymmetric, such as a microstrip, the partial self inductance of the two paths may be different.

However, when we relate the inductance per length of the line and the capacitance per length of the line to get the characteristic impedance, as in:

$$Z_0 = \sqrt{\frac{L}{C}}$$

it is the loop inductance per length that we are using. As we saw above, the loop inductance is composed of the self and the mutual: Loop = L(signal)$_{self}$ + L(return)$_{self}$ – 2 L_m. In most applications, where all you worry about is the characteristic impedance, it's not important what the actual partial self and mutual inductances are. The only term that contributes to a measurable quantify is the loop inductance.

However, in cases where the noise in the return path plays a role, as in the voltage created by common mode currents flowing in the plane that can contribute to EMI radiation, knowing the self inductance of the return path is important. The self inductance of the return path of stripline is less than in microstrip, which is why stripline offers better EMC performance than a microstrip line.

Loop Mutual Inductance

This loop inductance is really the self inductance of the loop, or the “loop self inductance”. You can see it coming: if there are two independent loops, there will be a mutual inductance between the two loops, which is the number of field lines from the current in one loop that completely surrounds the wire of the second loop.

When current in one loop changes, it will change the number of field lines around the second loop and induce noise in the second loop. The amount of noise created is $L_m \Delta I/\Delta t$. One of the coupling paths in two adjacent transmission lines is the mutual inductance between the current loops at the wavefront edge. The loops are composed of the signal paths and their return paths. When the return path is not a nice, uniform plane, the mutual inductance between two adjacent signal paths and their return can be large, as in the case of an IC package, or a connector. This is the most common origin of what we usually call simultaneous switching output noise or SSO noise. The most important way of reducing it is reducing the mutual inductance between the loops. This can be by moving them farther way or decreasing the area of each loop, for example.

When the return currents of two signal lines share the same conductor, the loop mutual inductance is dominated by the partial self inductance of the overlap region. This can be very large and is why you really want independent return path pins in a connector- a separate one for each signal path.

Summary

All the various flavors of inductance are directly related to the number of magnetic field lines around a conductor per amp of current. It’s importance is in being able to predict the induced noise across a conductor when currents change. Just referring to an inductance can be ambiguous. We now see that to be clear, we need to specific the source of the currents, as in the self inductance or mutual inductance. And we need to specific whether we are referring to part of the circuit with partial inductance or the whole circuit with loop inductance. In addition, there is also effective and equivalent inductance, but that's another story.

References

1. Bogatin, Eric, Beale, Bill and Light, David, “ Inductance Analysis of Chip Scale Packages”, Proceedings of CSP Int’l Conf, San Jose, CA, 1999, available for download from www.bogatinenterprises.com, in the Oct 1999 downloads section.

2. Grover, F. W. Inductance Calculations, 1973, Dover Publications. This is THE classic reference in inductance calculations. It is very technical and confusing, but is the source of many of the approximations offered for partial and loop inductance.

3. Walker, C. S, Capacitance, Inductance and Crosstalk Analysis. 1990, Artech House. Many useful approximations for loop inductance and capacitance.

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Bio of Dr. Eric Bogatin
Eric Bogatin received his BS in Physics from MIT and his Masters and Ph.D., in Physics from the University of Arizona in Tucson. For the past 19 years, he has been actively involved in the field of signal integrity and interconnect design, working at companies such as AT&T Bell Labs, Raychem Corp, Sun Microsystems, and Ansoft Corp.

Currently, Eric is the principle instructor with Bogatin Enterprises, specializing in training classes for signal integrity and interconnect design. Bogatin Enterprises is devoted to accelerating engineers up the learning curve by providing an entire continuing education curriculum of signal integrity and interconnect design classes. Eric has trained over 2,000 engineers and lectures worldwide on signal integrity topics.

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