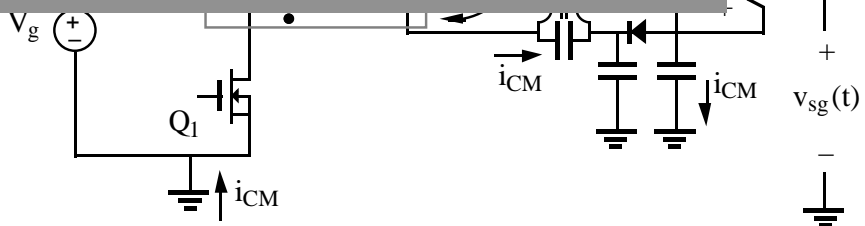
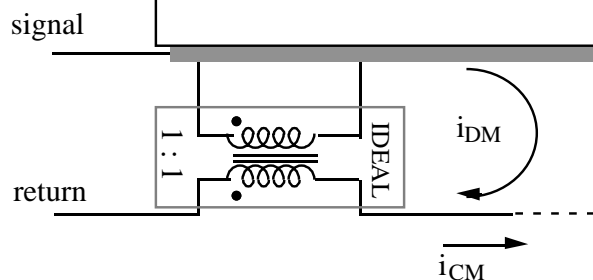
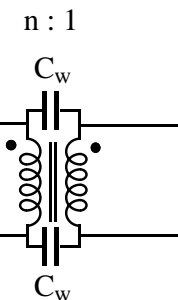


**Appendix 4  
on**

**EMI and Layout Fundamentals  
for Switched-Mode Circuits**

**R.W. Erickson**



# **EMI and Layout Fundamentals for Switched-Mode Circuits**

**R.W. Erickson**

- **Introduction**
- **Idealizing assumptions made in beginning circuits**
- **Inductance of wires**
- **Coupling of signals via impedance of ground connections**
- **Parasitic capacitances**
- **The common mode**
- **Common-mode and differential-mode filters**

# Introduction

**EMI (Electromagnetic Interference) is the unwanted coupling of signals from one circuit or system to another**

**Conducted EMI: unwanted coupling of signals via conduction through parasitic impedances, power and ground connections**

**Radiated EMI: unwanted coupling of signals via radio transmission**

**These effects usually arise from poor circuit layout and unmodeled parasitic impedances**

**Analog circuits rarely work correctly unless engineering effort is expended to solve EMI and layout problems**

**Sooner or later (or now!), the engineer needs to learn to deal with EMI**

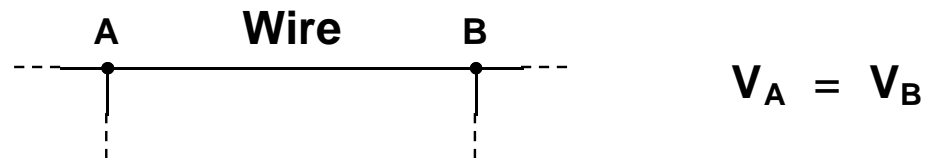
**The ideal engineering approach:**

- **figure out what are the significant EMI sources**
- **figure out where the EMI is going**
- **engineer the circuit layout to mitigate EMI problems**

**Build a layout that can be understood and analyzed**

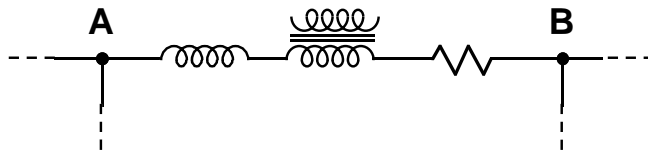
# Assumptions made in Circuits 101

## 1. Wires are perfect (equipotential) conductors



This assumption ignores

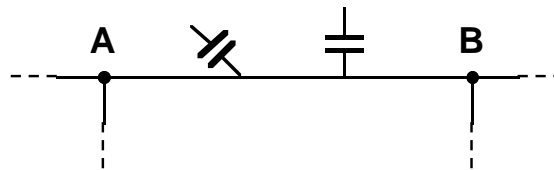
- wire resistance
- wire inductance
- mutual inductance with other conductors



## A related assumption:

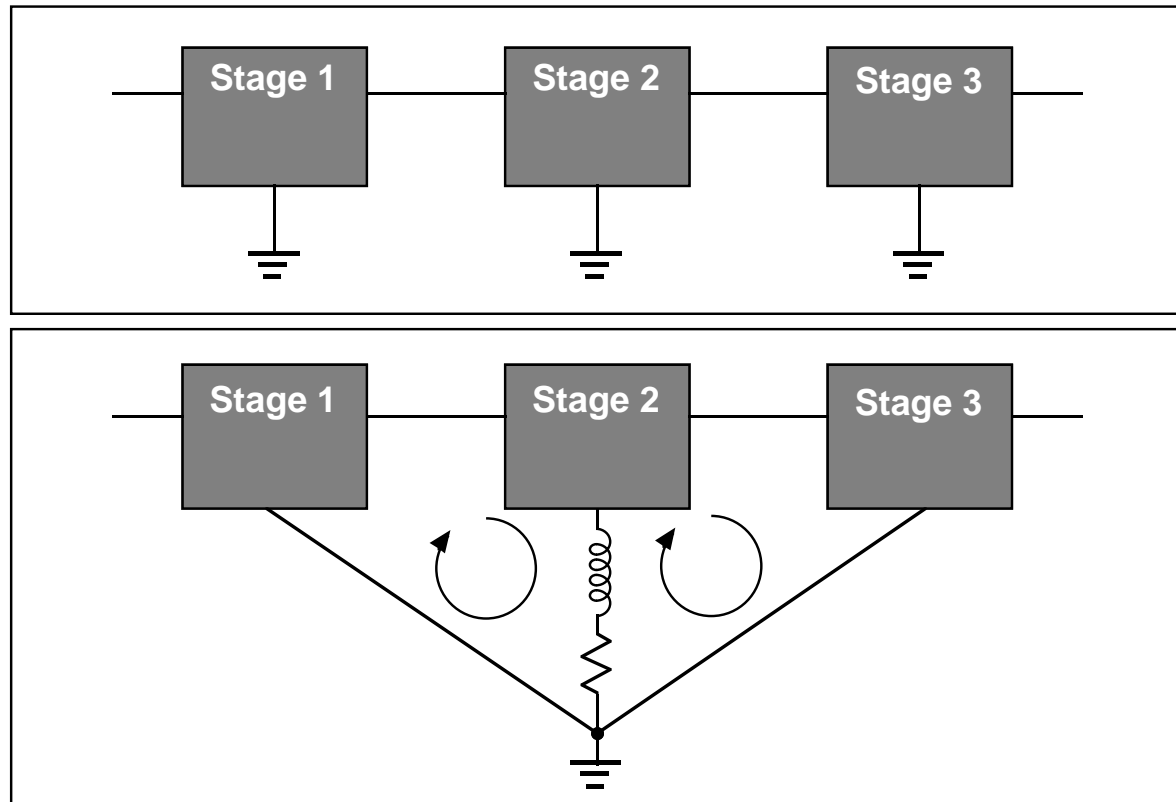
1a. The space surrounding a wire is a perfect insulator  
(dielectric constant = 0)

This assumption ignores capacitance between conductors



## 2. The ground (reference) node is at zero potential

Formally, this is a definition. But there is an implicit assumption that all parts of the system can be connected via ideal conductors to a common ground node. In practice, it is often quite difficult to ensure that each stage of a system operates with the same zero potential reference.



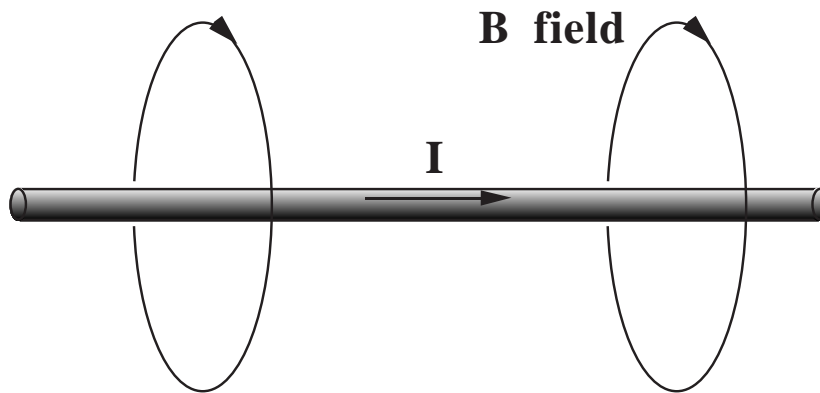
**We reinforce the problem by freely using the ground symbol**



**By use of this symbol, we avoid indicating how the actual wiring connection is made. In consequence, the possibility of conducted EMI via nonideal ground conductors is ignored**

# About inductance of wires

## Single wire in space



Self inductance

$$L = \frac{\lambda}{i}$$

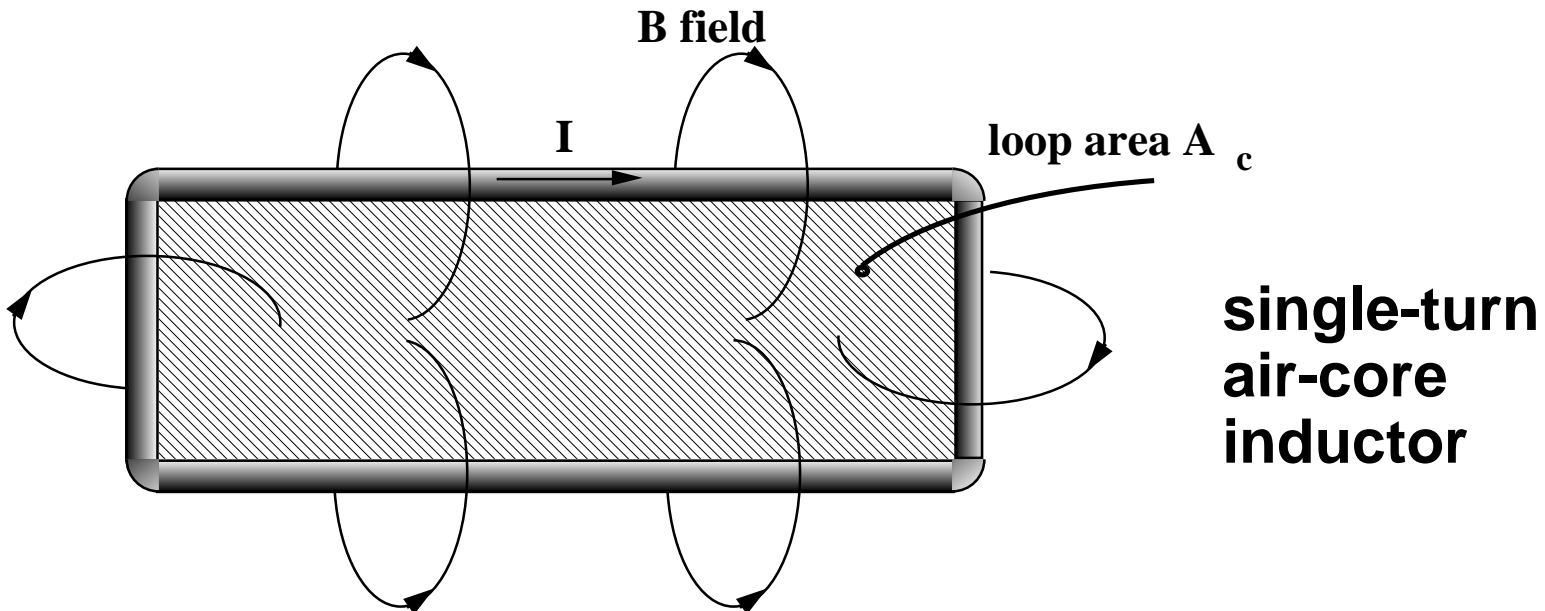
$$L = 0.00508 l \left( 2.303 \log_{10} \left( \frac{4l}{d} \right) - 0.75 \right) \mu\text{H}$$

Terman, *Radio Engineer's Handbook*, p. 48ff, 1943

$l$  = wire length  
 $d$  = wire diameter  
dimensions in inches

- Larger wire has lower inductance, because B-field must take longer path length around wire
- But how does the charge get back from end to beginning ? There is no closed loop, and so formula ignores area of loop
- Formula ignores effects of nearby conductors

**A more realistic scenario:  
current flows around a closed loop**



**Simple-minded inductance formula:**

$$L = \frac{\mu_0 A_c}{l_m}$$

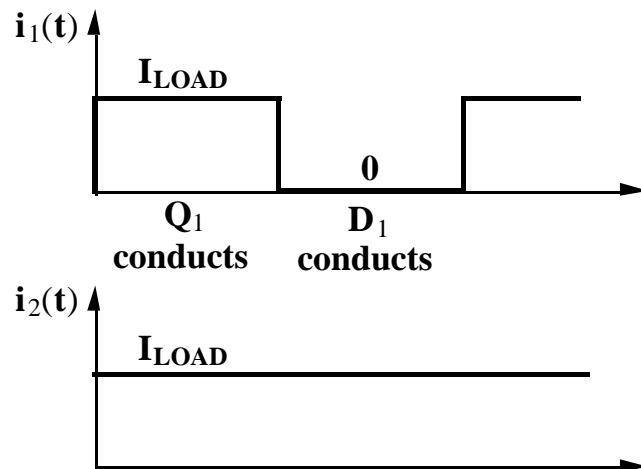
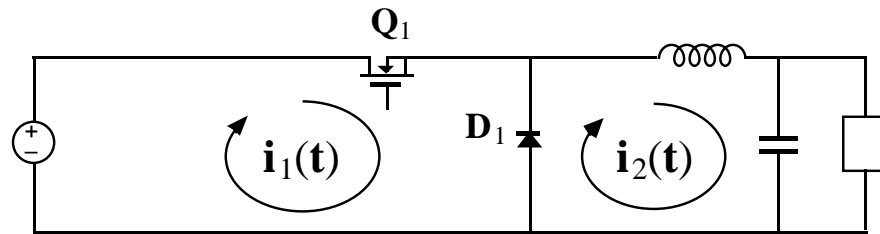
$$\mu_0 = 4\pi \cdot 10^{-7} \text{ H/m}$$

$l_m$  = **effective magnetic path length**

**To reduce inductance: reduce loop cross-sectional area (by routing of wires), or increase path length (use larger wire).**

# Example: Buck converter

Use loop analysis



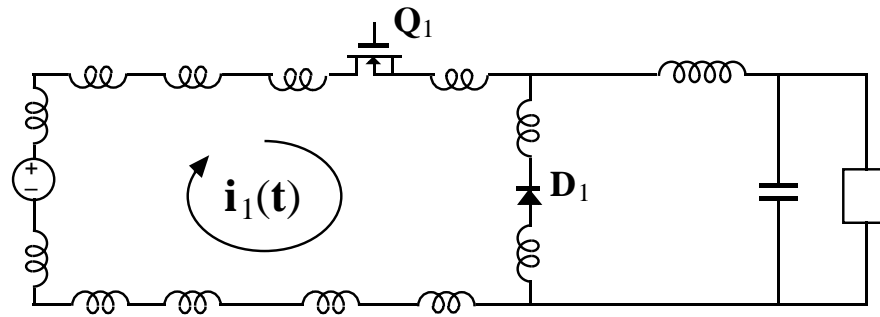
switched input current  $i_1(t)$  contains large high frequency harmonics

—hence inductance of input loop is critical  
inductance causes ringing, voltage spikes, switching loss, generation of B- and E-fields, radiated EMI

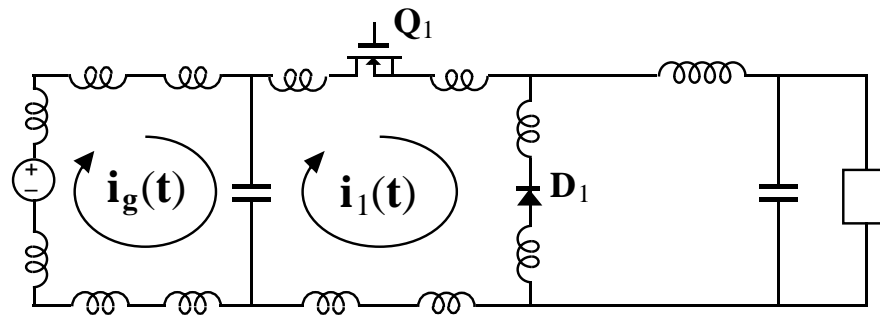
the second loop contains a filter inductor, and hence its current  $i_2(t)$  is nearly dc

—hence additional inductance is not a significant problem in the second loop

**Parasitic inductances of input loop explicitly shown:**

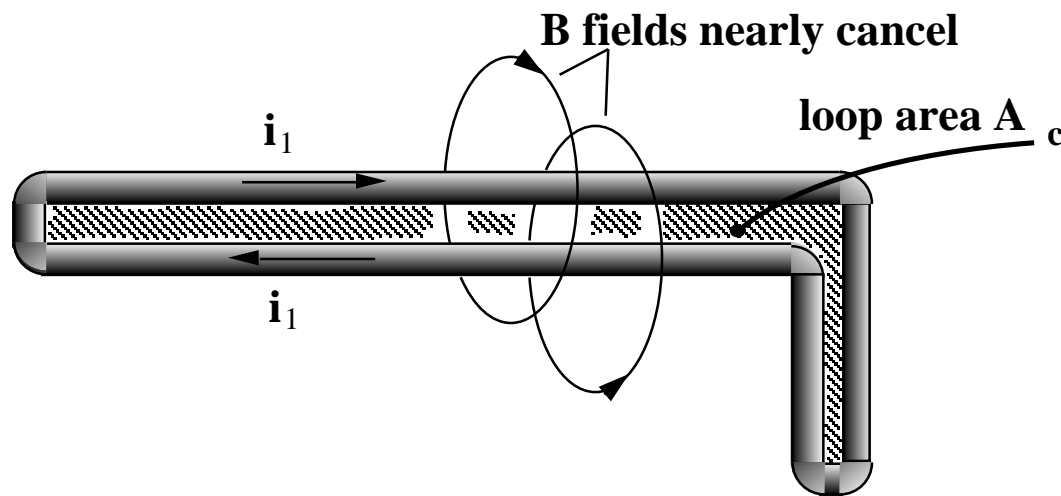
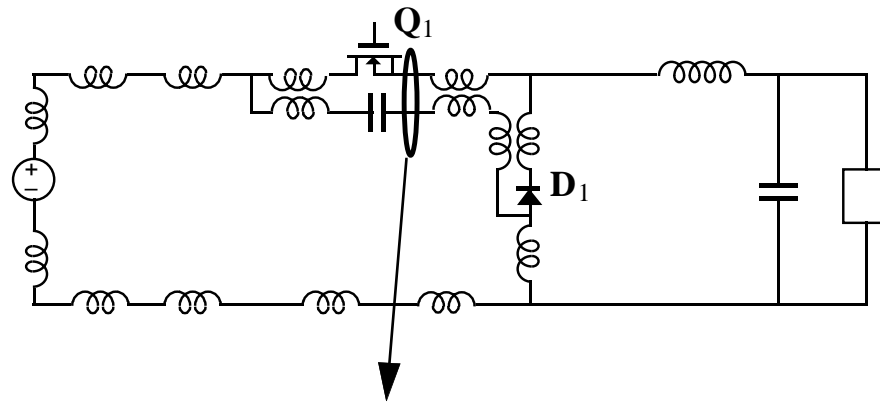


**Addition of bypass capacitor confines the pulsating current to a smaller loop:**



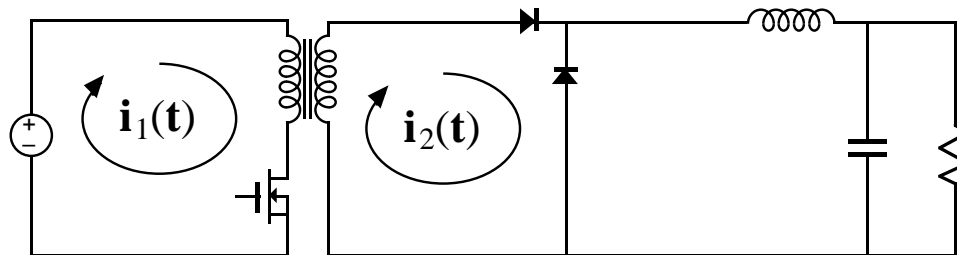
**high frequency currents are shunted through capacitor instead of input source**

Even better: minimize area of the high frequency loop, thereby minimizing its inductance

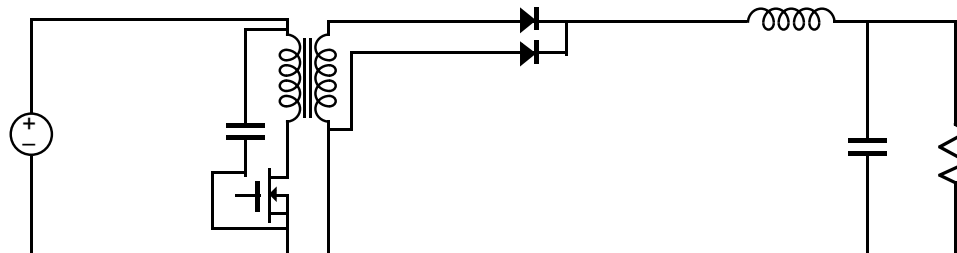


# Forward converter

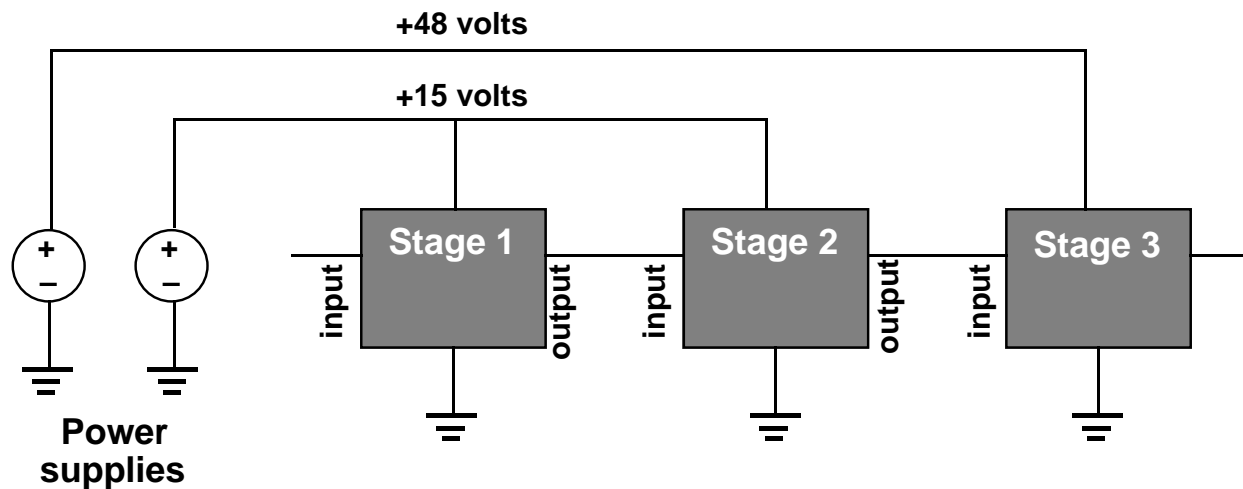
Two critical loops:



Solution:

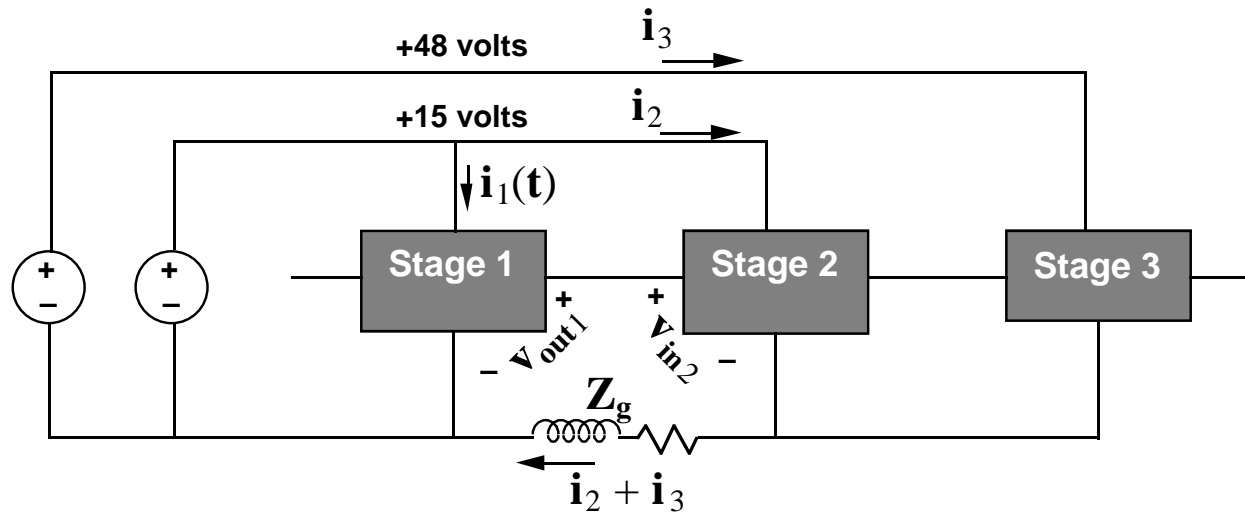


# Unwanted coupling of signals via impedance of ground connections



- All currents must flow in closed paths: determine the entire loop in which large currents flow, including the return connections
- Ground (zero potential) references may not be the same for every portion of the system

**Example: suppose the ground connections are**

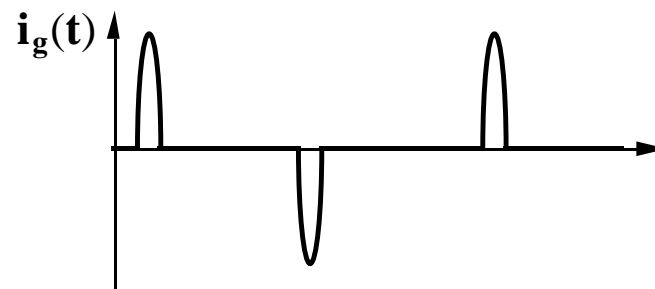
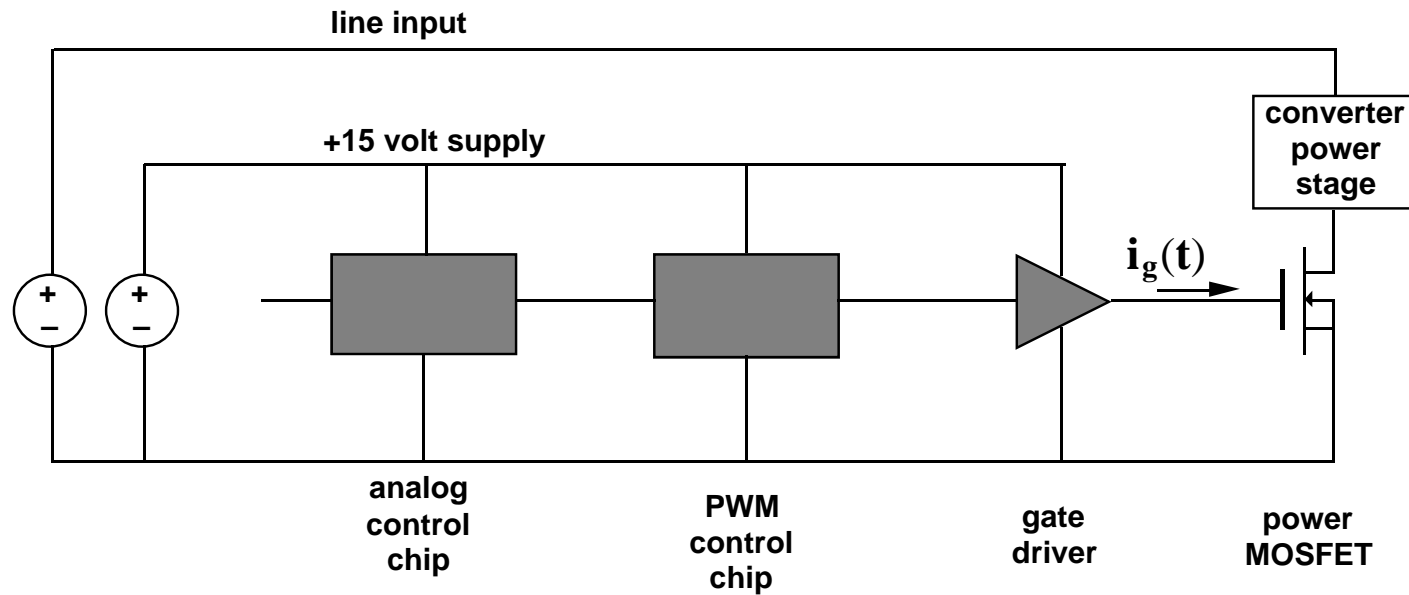


$$V_{in2} = V_{out1} - Z_g (i_2 + i_3)$$

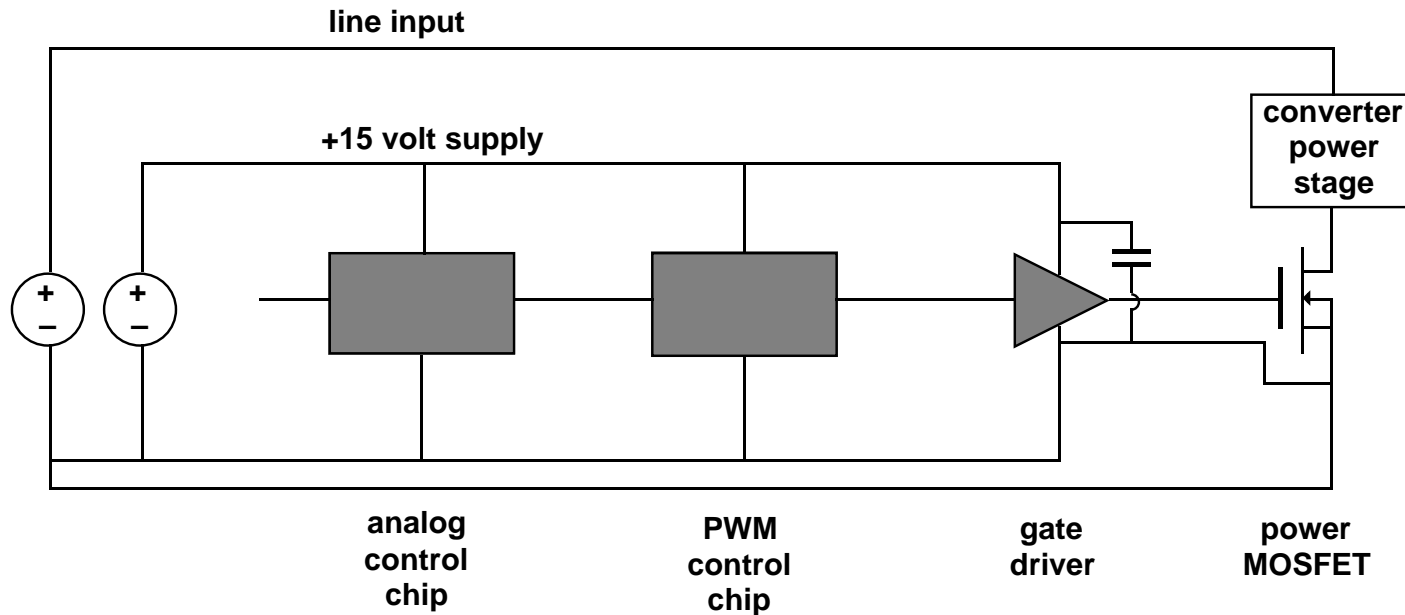
**“Noise” from stages 2 and 3 couples into the input to stage 2**

**This represents conducted EMI, or specifically corruption of the ground reference by system currents**

# Example: gate driver



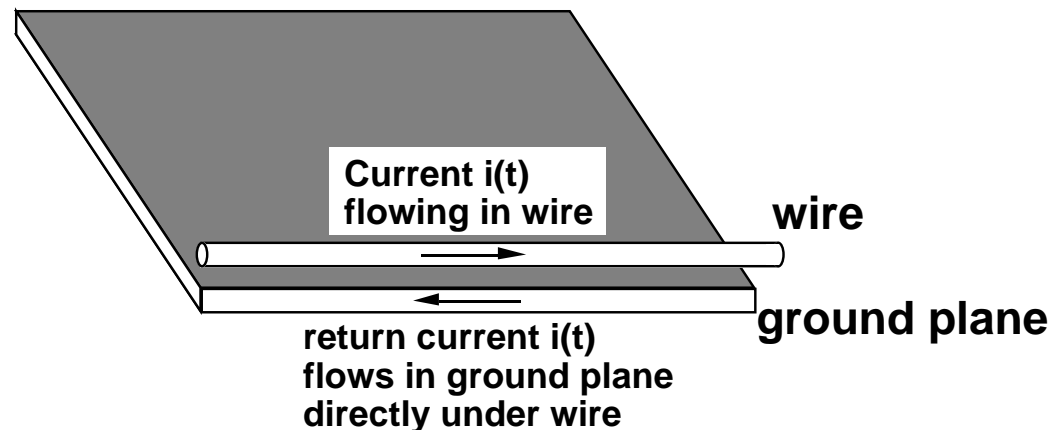
## Solution: bypass capacitor and close coupling of gate and return leads



High frequency components of gate drive current are confined to a small loop

A dc component of current is still drawn output of 15V supply, and flows past the control chips. Hence, return conductor size must be sufficiently large

# About ground planes



**Inductance of return connections is minimized**

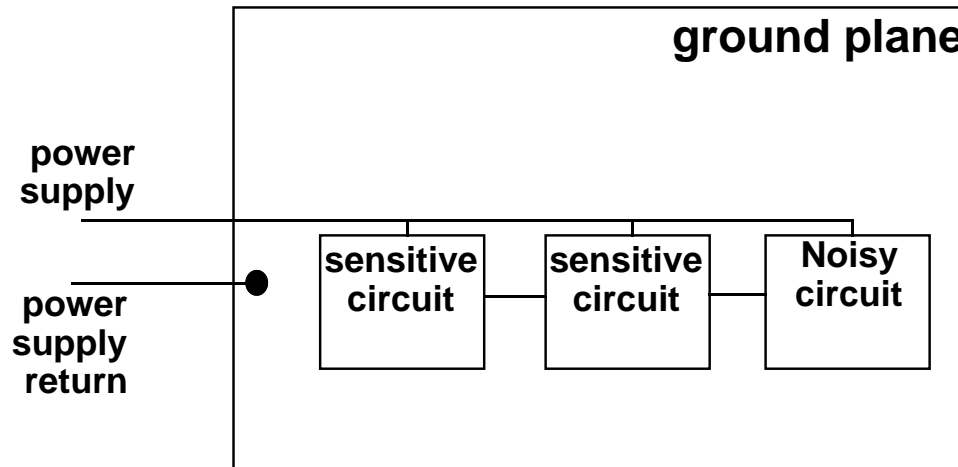
**Hence ground planes tend to exhibit lower impedance ground connections, and more nearly equipotential ground references**

**Ground planes are especially effective in the analog control portions of switching regulator circuits**

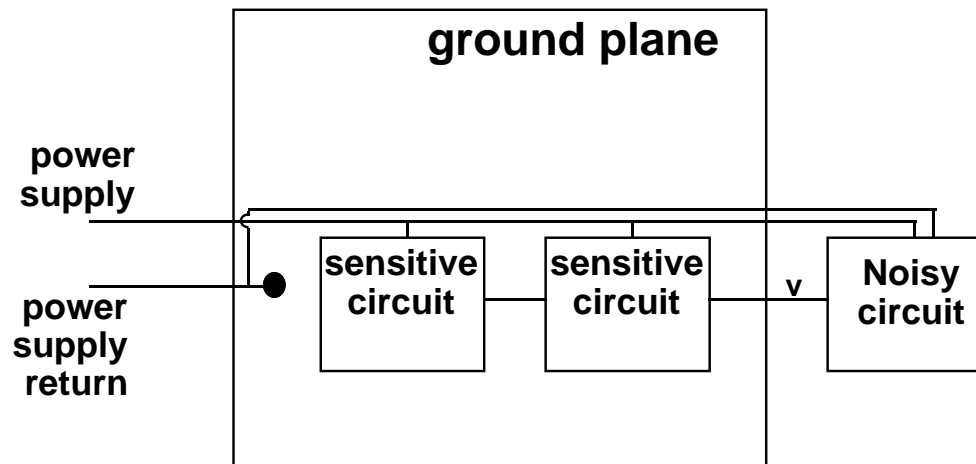
**But it is still possible to observe significant coupling of noise in ground, by**

- **poor layout of ground plane, or**
- **high resistance of ground plane**

# A poor ground plane layout



Return current of noisy circuit runs underneath sensitive circuits, and can still corrupt their ground references

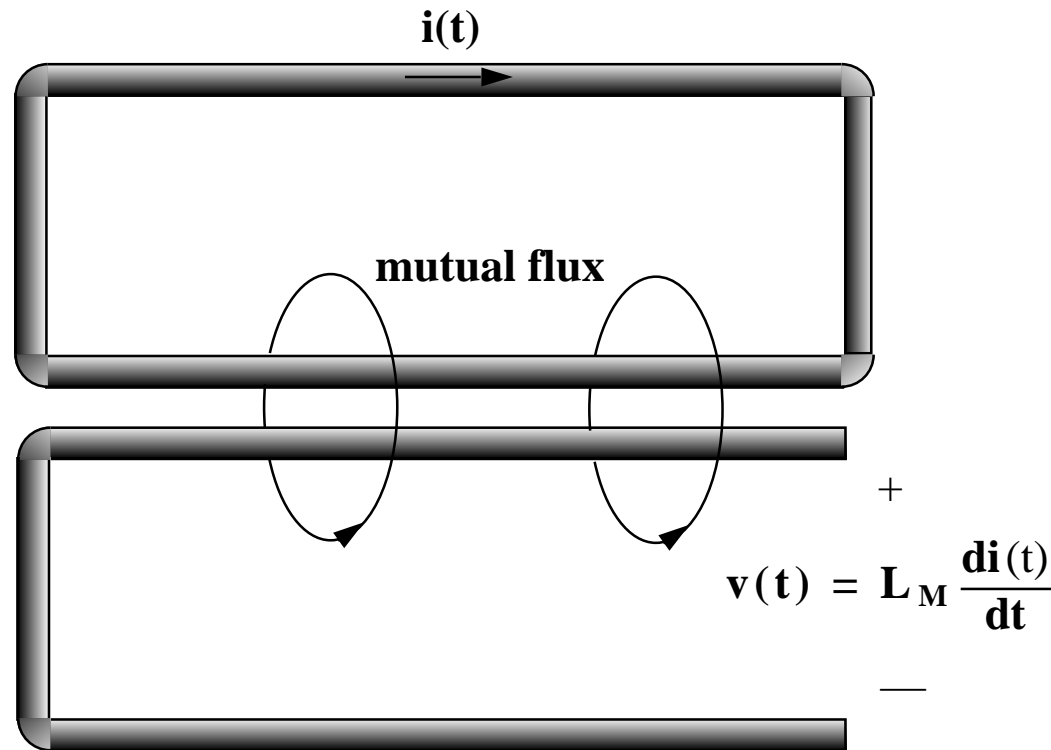


A solution is to remove the noisy circuit from the ground plane. One could then run a separate ground wire for the noisy circuit. The only drawback is that noise can be coupled into the input signal  $v$ .

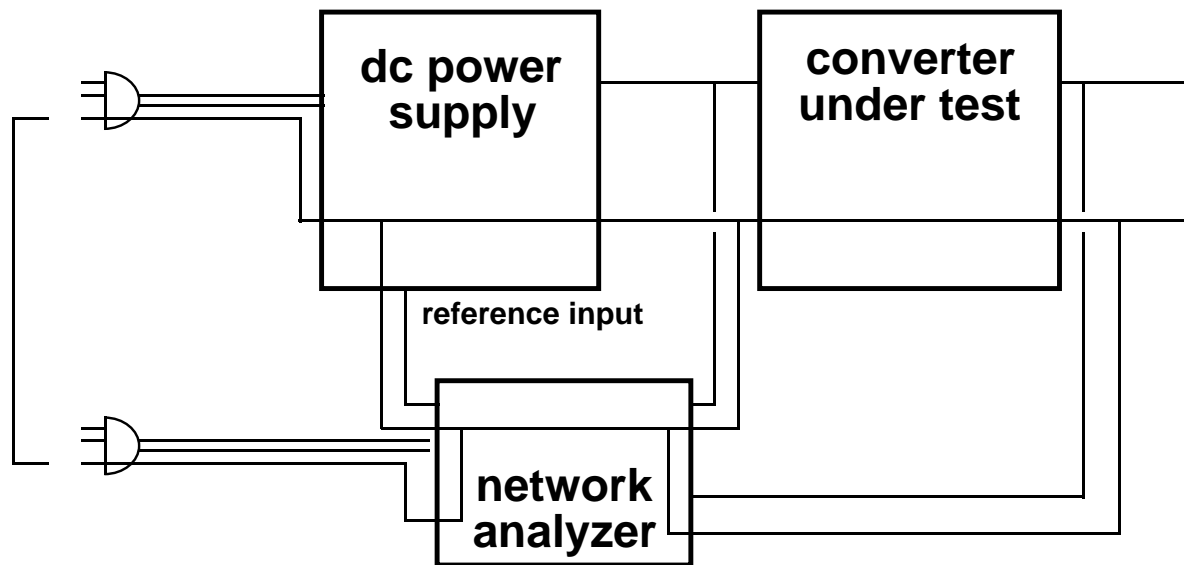
# Coupling of signals via magnetic fields

Loop containing ac current  $i(t)$  generates B field

which links another conductor, inducing an unwanted voltage  $v(t)$



**This phenomenon can sometimes be a problem when ground loops are present. Circulating ground currents are then induced, which lead to variations in the ground reference potential**



**Measurement of audiosusceptibility: observed unusual and unexpected results**

**Fixed by breaking ground loops**

**Audiosusceptibility then was as expected**

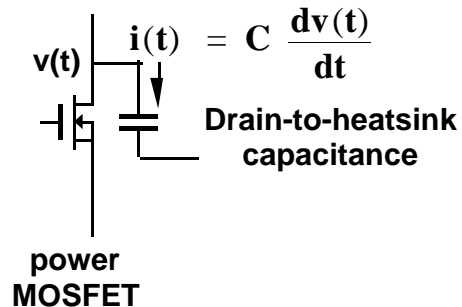
# Stray capacitances

Most significant at high voltage points in circuit

Two major sources of EMI:

- Transformer interwinding capacitance
- MOSFET drain-to-heatsink capacitance

## *Drain-to-heatsink capacitance*



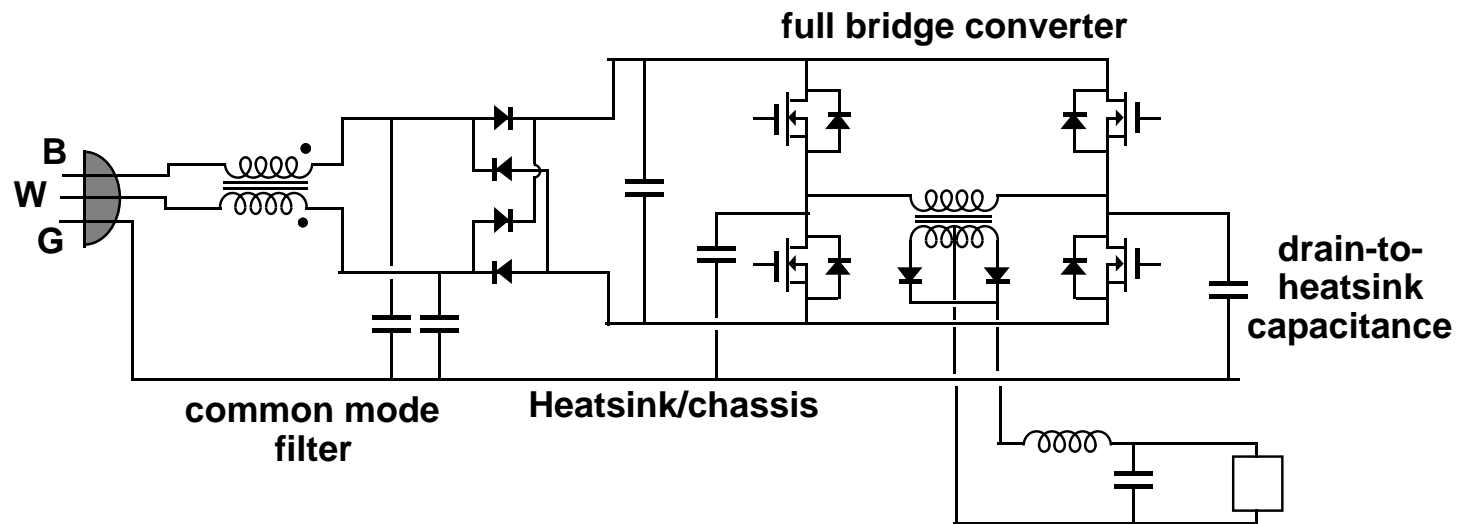
When the switched drain voltage is applied to this capacitance, current spikes must flow.

The currents must flow in a closed path (a loop). What is the loop in your circuit?

To control the effects of these currents,

- provide a short path for them to return to their origin
- add common-mode filters
- slow down switching times

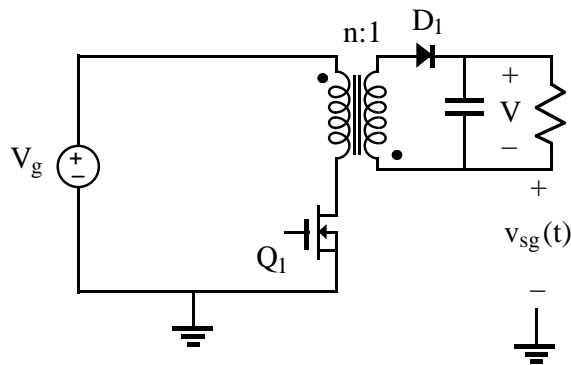
# Common mode noise generation by drain-to-heatsink capacitance



# Common mode noise generation

## by transformer interwinding capacitance

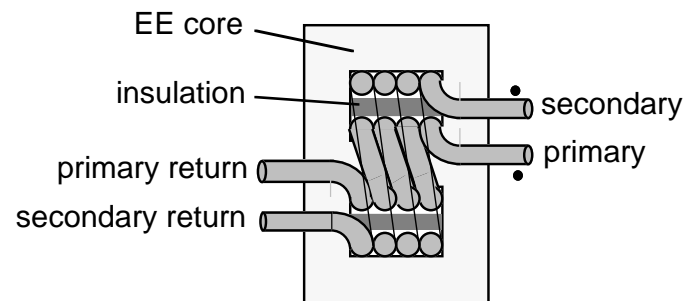
### *Flyback converter example*



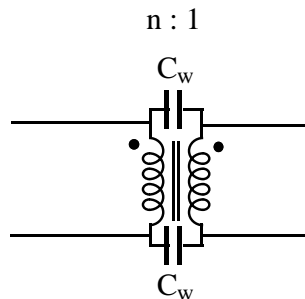
Transformer interwinding capacitance causes currents to flow between the isolated (primary and secondary) sides of the transformer, and can cause the secondary-side ground voltage to switch at high frequency:  $v_{sg}(t)$  contains a high-frequency component.

# Modeling transformer interwinding capacitance

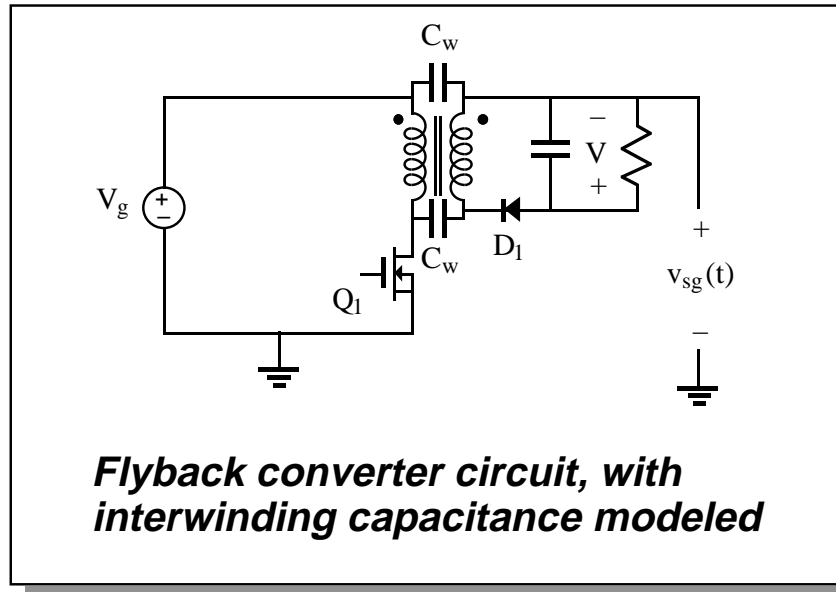
Suppose the transformer is wound as follows:



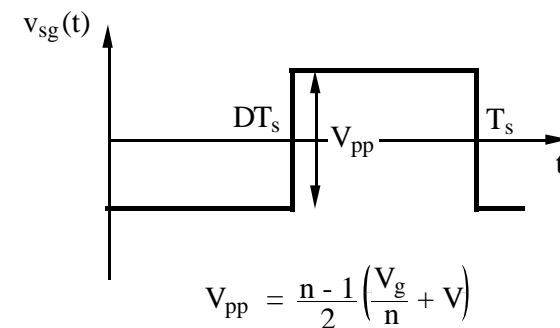
A simple lumped element model, including interwinding capacitance:



# Flyback converter ground potentials



One can solve the circuit to find the high-frequency ac component of  $v_{sg}(t)$ . The result is

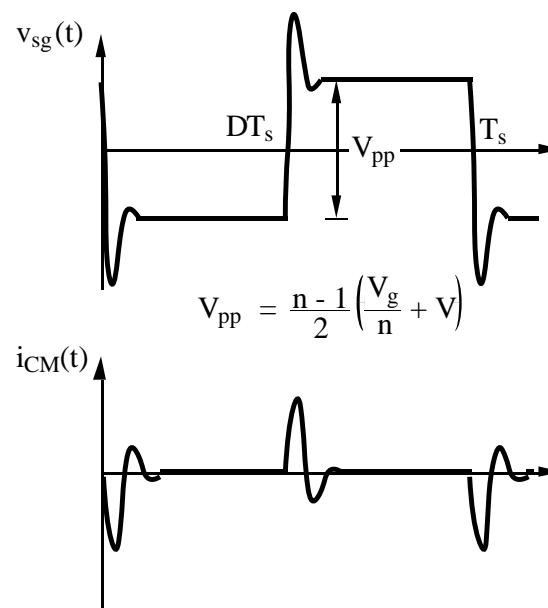
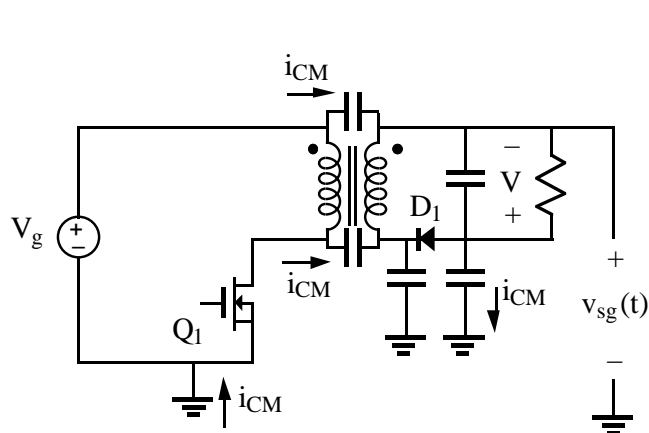


The secondary ground potential switches at high frequency with respect to the primary ground.

The peak-peak voltage  $V_{pp}$  is typically approximately equal to  $V_g$ .  $v_{sg}(t)$  can also have a dc component, not predicted by the circuit model.

## Secondary-side stray capacitances now lead to common-mode currents

*Example: diode case-to-heat sink capacitance*



These currents usually corrupt the ground reference voltage

# Discussion

- **Transformers can successfully provide dc and low-frequency ac isolation**
- **Transformer interwinding capacitances couple the primary and secondary voltages, greatly reducing the high-frequency ac isolation and leading to common-mode currents and conducted EMI**

**Some possible solutions:**

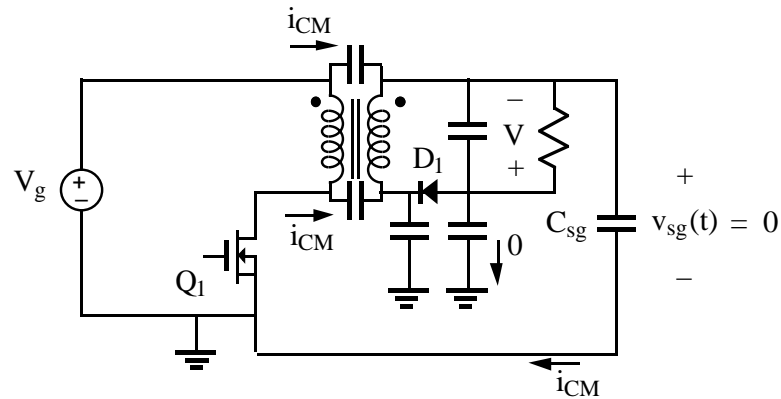
- **Redesign the transformer to reduce the interwinding capacitance. This usually leads to increased leakage inductance**
- **Add common-mode filters:**

**Capacitors which connect the primary- and secondary-side grounds**

**Common-mode filter inductors**

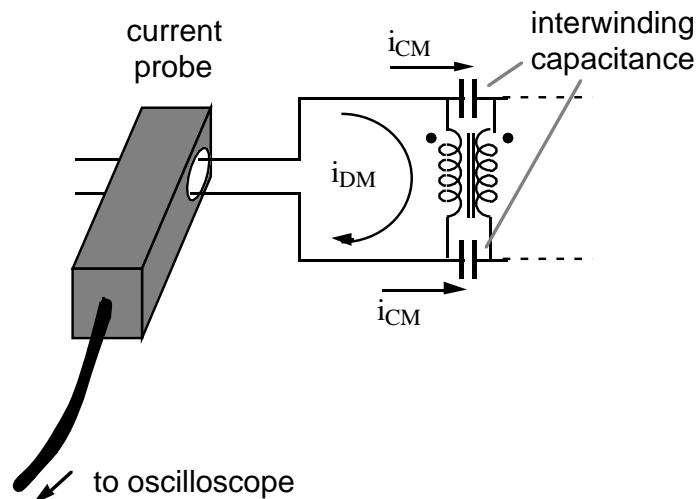
**This greatly reduces conducted EMI, and can also reduce radiated EMI. But the capacitors do not allow the secondary ground potential to switch at high frequency.**

## Addition of capacitance between primary and secondary grounds



Capacitor  $C_{sg}$  is much larger than the stray capacitances, and so nearly all of the common-mode current flows through  $C_{sg}$ . If  $C_{sg}$  is sufficiently large, then it will have negligible voltage ripple, and  $v_{sg}(t)$  will no longer contain a high-frequency component.

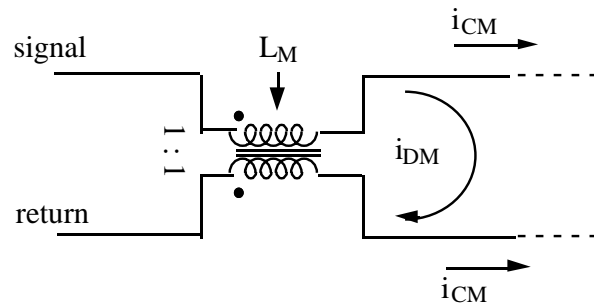
# Measurement of common mode current



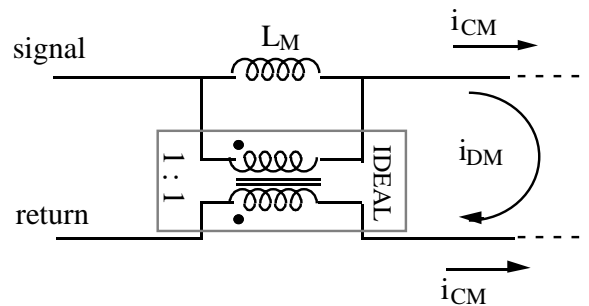
The common mode current due to transformer interwinding capacitance can be easily measured using a current probe

The differential-mode current  $i_{DM}(t)$  cancels out, and the oscilloscope will display  $2i_{CM}(t)$ .

# A Common-Mode Choke

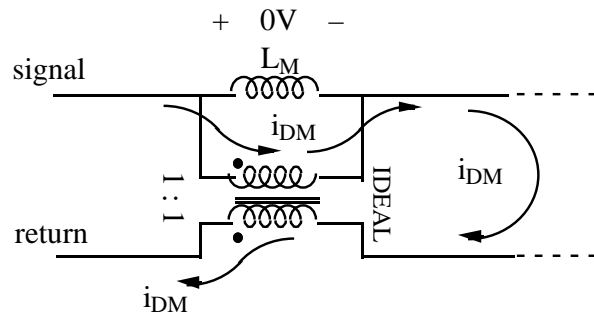


Equivalent circuit, including magnetizing inductance:



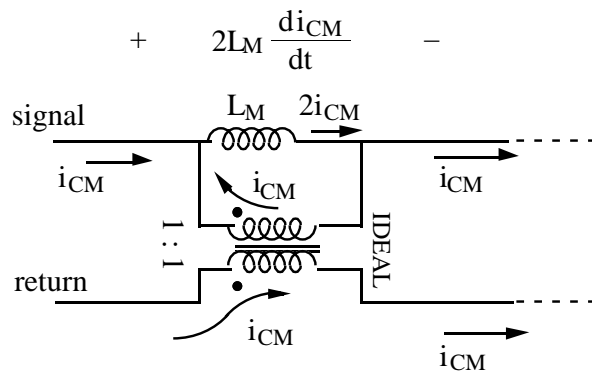
# Operation of Common-Mode Choke

## Differential mode



$i_{DM}$  cancels out in windings, with no net magnetization of core. To the extent that the leakage inductance can be neglected, the common-mode choke has no effect on the differential-mode currents.

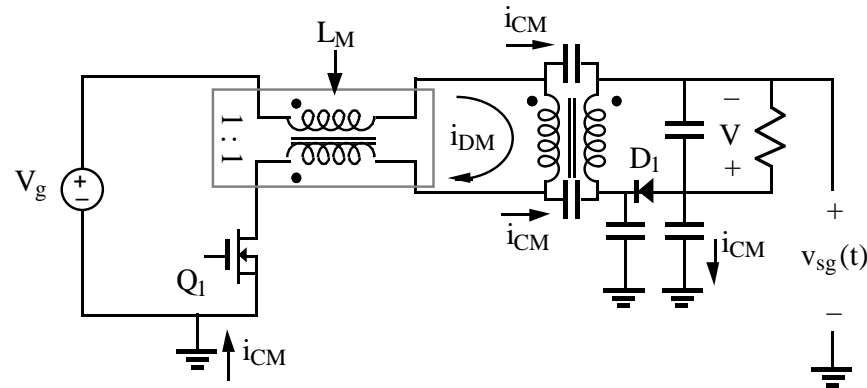
## Common mode



The common-mode currents effectively add, magnetizing the core. The common-mode choke presents inductance  $L_M$  to filter these currents.

# Use of a common-mode choke

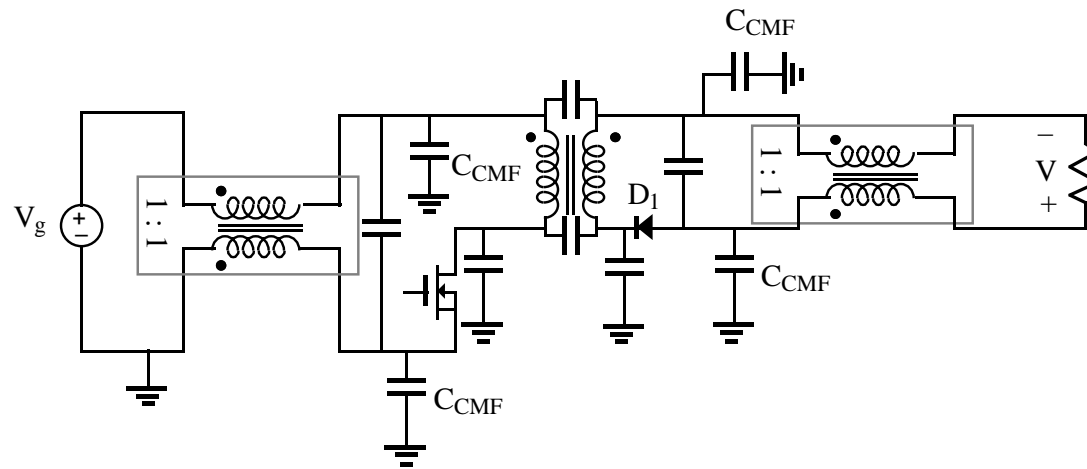
to reduce the magnitude of currents  
in transformer interwinding capacitances



Common-mode choke inserts inductance  $L_M$  to oppose flow of high-frequency common-mode currents

# Use of common-mode chokes

to filter the power supply input and output

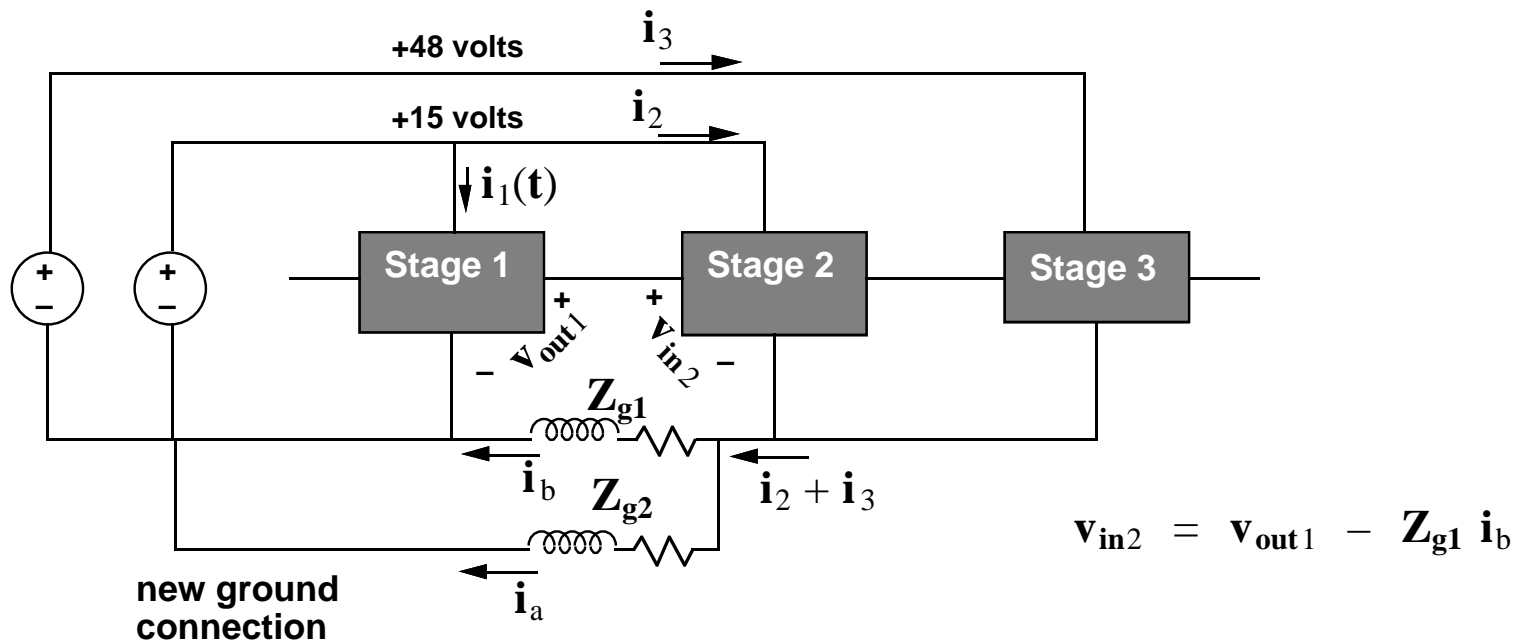


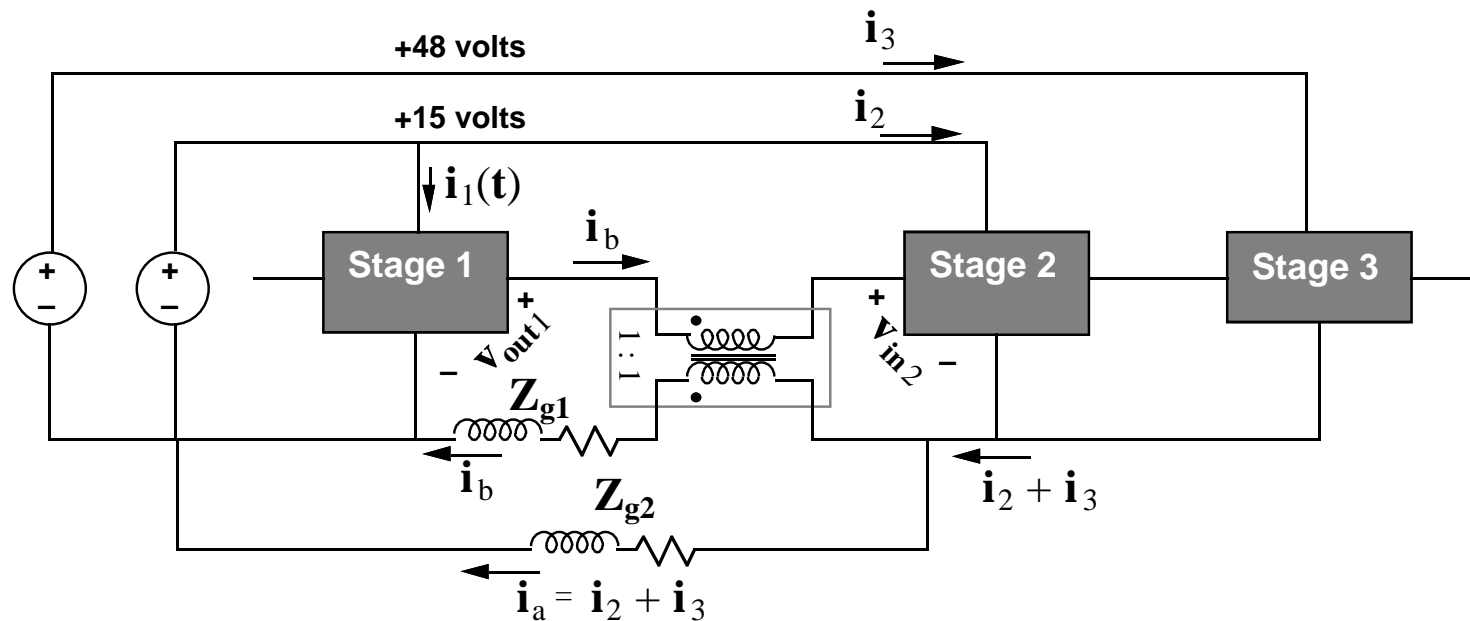
The common-mode chokes, along with the capacitors  $C_{CMF}$ , form two-pole low pass filters which oppose the flow of high-frequency common-mode currents

# Use of a common-mode choke to prevent corruption of ground reference voltage

Back to example of slide #14:

Attempt to prevent coupling of signal ( $i_2 + i_3$ ) into input signal  $v_{in2}$  by adding another ground connection, for conduction of return current ( $i_2 + i_3$ ). This requires that  $i_a = (i_2 + i_3)$ .





The common-mode choke forces the high frequency return current ( $i_2 + i_3$ ) to flow through the alternate ground path:  $i_a = (i_2 + i_3)$ . The return current  $i_b$  is equal to the signal current flowing between stages 1 and 2.

# Summary

**EMI ("Noise") is caused by the violation of idealizing assumptions:**

**Imperfect conductors**

**Corruption of zero-potential ground reference**

**Stray capacitances**

**Inductance of wires**

**Keep areas of high frequency loops as small as possible**

**Coupling of signals via impedance of ground connections**

**Steer ground currents away from sensitive circuits**

**Examples: power return, gate drive return, coupling of signals  
from one stage to the next**

**Use ground planes in sensitive analog portions of system**

**Coupling of signals via magnetic fields**

**Ground loops and circulating ground currents**

**Example: audiosusceptibility measurement**

## **Coupling of signals via electric fields**

**Stray capacitances**

**Example: drain-to- heatsink capacitance**

**Example: transformer interwinding capacitances**

## **Common mode noise**

**Usually caused by stray capacitances**

**Can be filtered using common-mode chokes and common-mode filter capacitors**

**It is possible to figure out where the EMI is being generated, and to engineer the circuit to mitigate its effects**