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THE CIRCUIT DESIGNER'S COMPANION

Third Edition

Peter Wilson

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Newnes is an imprint of Elsevier
The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, UK
225 Wyman Street, Waltham, MA 02451, USA

First edition 1991
Second edition 2005
Third edition 2012

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British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Control Number: 2011940053

ISBN: 978-0-08-097138-4

For information on all Newnes publications visit our website at www.elsevierdirect.com

Printed and bound in the United Kingdom

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Introduction

When I was first approached to produce a third edition of *The Circuit Designer's Companion*, I was at first reluctant to "mess with it". It is rare to have a companion book that is not just a textbook, or a handbook, but is seen in many respects to contain all the essential information that a "real" circuit designer needs to not only produce a working circuit, but to enable that designer to understand all the related topics that make the design robust, tolerant to noise and temperature, and able to operate in the system that it was designed for. This book is a rare example of just that, and there is no other comparable text that provides such a broad range of design skills to be passed on to the next generation of circuit designers.

It is interesting to note that twenty-one years on from the original edition of this book there is no diminution of demand for analog and mixed signal design skills, however, most universities and colleges still teach a syllabus in electronics that is dominated by digital design techniques. The comment made by Tim in the introduction to the first edition that analog electronics were "hard" and there was a reluctance to embark on analog electronics could have been written this year, rather than two decades ago! During the revision of this book, it was also interesting to note that much of the content was still completely valid in today's electronic systems, albeit some of the individual technology elements have of course moved on, with many of the fundamental concepts being essentially the same.

Peter Wilson

INTRODUCTION TO THE FIRST EDITION (TIM WILLIAMS, 1990)

Electronic circuit design can be divided into two areas: the first consists in designing a circuit that will fulfil its specified function, sometimes, under laboratory conditions; the second consists in designing the same circuit so that every production model of it will fulfil its specified function, and no other undesired and unspecified function, always, in the field, reliably over its lifetime. When related to circuit design skills, these two areas coincide remarkably well with what engineers are taught at college – basic circuit theory, Ohm's law, Thévenin, Kirchhoff, Norton, Maxwell and so on – and what they learn on the job – that there is no such thing as the ideal component, that printed circuits are more than just a collection of tracks, and that electrons have an unfortunate habit of never doing exactly what they're told.

This book has been written with the intention of bringing together and tying up some of the loose ends of analog and digital circuit design, those parts that are never mentioned in the textbooks and rarely admitted elsewhere. In other words, it relates to the second of the above areas.

Its genesis came with the growing frustration experienced as a senior design engineer, attempting to recruit people for junior engineer positions in companies whose foundations rested on analog design excellence. Increasingly, it became clear that the people I and my colleagues were interviewing had only the sketchiest of training in electronic circuit design, despite offering apparently sound degree-level academic qualifications. Many of them were more than capable of hooking together a microprocessor and a few large-scale functional block peripherals, but were floored by simple questions such as the nature of the p–n junction or how to go about resistor tolerancing. It seems that this experience is by no means uncommon in other parts of the industry.

The colleges and universities can hardly be blamed for putting the emphasis in their courses on the skills needed to cope with digital electronics, which is after all becoming more and more pervasive. If they are failing industry, then surely it is industry's job to tell them and to help put matters right. Unfortunately it is not so easy. A 1989 report from Imperial College, London, found that few students were attracted to analog design, citing inadequate teaching and textbooks as well as the subject being found "more difficult". Also, teaching institutions are under continuous pressure to broaden their curriculum, to produce more "well-rounded" engineers, and this has to be at the expense of greater in-depth coverage of the fundamental disciplines.

Nevertheless, the real world is obstinately analog and will remain so. There is a disturbing tendency to treat analog and digital design as two entirely separate disciplines, which does not result in good training for either. Digital circuits are in reality only over-driven analog ones, and anybody who has a good understanding of analog principles is well placed to analyze the more obscure behavior of logic devices. Even apparently simple digital circuits need some grasp of their analog interactions to be designed properly, as Chapter 6 of this book shows. But also, any product which interacts with the outside world via typical transducers must contain at least some analog circuits for signal conditioning and the supply of power. Indeed, some products are still best realized as all-analog circuits. Jim Williams, a well-known American linear circuit designer (who bears no relation to the author of the first two editions of this book), put it succinctly when he said "wonderful things are going on in the forgotten land between ONE and ZERO. This is Real Electronics."

Because analog design appears to be getting less popular, those people who do have such skills will become more sought-after in the years ahead. This book is meant to be a tool for any aspiring designer who wishes to develop these skills. It assumes at least a background in electronics design; you will not find in here more than a minimum of basic circuit theory. Neither will you find recipes for standard circuits, as there are many other excellent books which cover those areas. Instead, there is a serious treatment of those topics which are "more difficult" than building-block electronics: grounding, temperature effects, EMC, component sourcing and characteristics, the imperfections of devices, and how to design so that someone else can make the product.

I hope the book will be as useful to the experienced designer who wishes to broaden his or her background as it will to the neophyte fresh from college who faces a first job in industry with trepidation and excitement. The traditional way of gaining experience is to learn on-the-job through peer contact, and this book is meant to enhance rather than supplant that route. It is offered to those who want their circuits to stand a greater chance of working first time every time, and a lesser chance of being completely redesigned after six months. It does not claim to be conclusive or complete. Electronic design, analog or digital, remains a personal art, and all designers have their own favorite tricks and their own dislikes. Rather, it aims to stimulate and encourage the quest for excellence in circuit design.

I must here acknowledge a debt to the many colleagues over the years who have helped me towards an understanding of circuit design, and who have contributed towards this book, some without knowing it: in particular Tim Price, Bruce Piggott and Trevor Forrest. Also to Joyce, who has patiently endured the many brainstorms that the writing of it produced in her partner.

INTRODUCTION TO THE SECOND EDITION (TIM WILLIAMS, 2004)

The first edition was written in 1990 and eventually, after a good long run, went out of print. But the demand for it has remained. There followed a period of false starts and much pestering, and finally the author was persuaded to pass through the book once more to produce this second edition. The aim remains the same but technology has progressed in the intervening fourteen years, and so a number of anachronisms have been corrected and some sections have been expanded. I am grateful to those who have made suggestions for this updating, especially John Knapp and Martin O'Hara, and I hope it continues to give the same level of help that the first edition evidently achieved.

INTRODUCTION TO THE THIRD EDITION (PETER WILSON, 2012)

The third edition of the book has really been an exercise of revision rather than revolution, and I have tried to keep the philosophy the same as the original author intended. As with the second edition, the aim has been to update the technological aspects in the book, expand some sections and offer a slightly different personal perspective to hopefully further enhance the book. I am very grateful to Tim Williams for allowing me to make these revisions, and for his discussions about the book's previous editions. I also acknowledge the advice, teaching and knowledge of many friends and colleagues over the past three decades which have provided much insight into the art of analog electronics, including my father, Tom Wilson, Frank Fisher while at Ferranti, Professor Alan Mantooth at the University of Arkansas, and Dr Neil Ross and Dr Reuben Wilcock, at the University of Southampton. I must also thank my wife, Caroline, who has tolerated my fascination with electronics for many years. I hope that further generations of electronic designers will find this edition useful and that the book will continue to provide the assistance and help to circuit designers that the previous editions have done over the last two decades.

CHAPTER

Grounding and wiring

1

CHAPTER OUTLINE

The Circuit Designer's Companion. DOI: 10.1016/B978-0-08-097138-4.00001-X

1.1 GROUNDING

A fundamental property of any electronic or electrical circuit is that the voltages present within it are referenced to a common point, conventionally called the ground. This term is derived from electrical engineering practice, when the reference point is often taken to a copper spike literally driven into the ground. This point may also be a connection point for the power to the circuit, and it is then called the 0 V (nought-volt) rail, and ground and 0 V are frequently (and confusingly) synonymous. Then, when we talk about a five-volt supply or a minus-twelve-volt supply or a two-and-a-half-volt reference, each of these are referred to the 0 V rail.

At the same time, ground is *not* the same as 0 V. A ground wire connects equipment to earth for safety reasons, and does not carry a current in normal operation. However, in this chapter the word “grounding” will be used in its usual sense, to include both safety earths and signal and power return paths.

Perhaps the greatest single cause of problems in electronic circuits is that 0 V and ground are taken for granted. The fact is that in a working circuit there can only ever be one point which is truly at 0 V; the concept of a “0 V rail” is in fact a contradiction in terms. This is because any practical conductor has a finite non-zero resistance and inductance, and Ohm’s law tells us that a current flowing through anything other than a zero impedance will develop a voltage across it. A working circuit will have current flowing through those conductors that are designated as the 0 V rail and therefore, if any one point of the rail is actually at 0 V (say, the power supply connection) the rest of the rail will *not* be at 0 V. This can be illustrated with the example in Figure 1.1.

Now, after such a trenchant introduction, you might be tempted to say well, there are millions of electronic circuits in existence, they must all have 0 V rails, they seem to work well enough, so what's the problem? Most of the time there is no problem. The impedance of the 0 V conductor is in the region of milliohms, the current levels are milliamps, and the resulting few hundred microvolts drop doesn't offend the circuit at all; 0 V plus 500 μV is close enough to 0 V for nobody to worry.

The difficulty with this answer is that it is then easy to forget about the 0 V rail and assume that it is 0 V under all conditions, and subsequently be surprised when a circuit oscillates or otherwise doesn't work. Those conditions where trouble is likely to arise are:

- where current flows are measured in amps rather than milli- or microamps;
- where the 0 V conductor impedance is measured in ohms rather than milliohms;
- where the resultant voltage drop, whatever its value, is of a magnitude or in such a configuration as to affect the circuit operation.

When to consider grounding

One of the attributes of a good circuit designer is to know when these conditions need to be carefully considered and when they may be safely ignored. A frequent complication is that you as circuit designer may not be responsible for the circuit's layout, which is handed over to a layout draughtsman (who may in turn delegate many routing decisions to a software package). Grounding is always sensitive to layout, whether of discrete wiring or of printed circuits, and the designer must have some knowledge of and control over this if the design is not to be compromised.

The trick is always to be sure that you know where ground return currents are flowing, and what their consequences will be; or, if this is too complicated, to make sure that wherever they flow, the

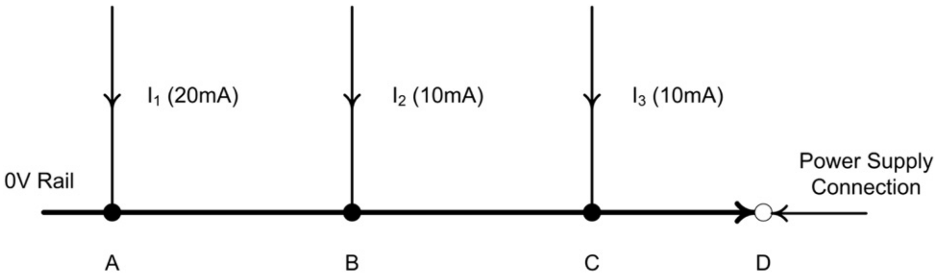

FIGURE 1.1 Voltages along the 0 V rail

Assume the 0 V conductor has a resistance of 10 mΩ/inch and that points A, B, C and D are each one inch apart. The voltages at points A, B and C referred to D are:

$$V_C = (I_1 + I_2 + I_3) \times 10\,\text{m}\Omega = 400\,\mu\text{V}$$

$$V_B = V_C + (I_1 + I_2) \times 10\,\text{m}\Omega = 700\,\mu\text{V}$$

$$V_A = V_B + (I_1) \times 10\,\text{m}\Omega = 900\,\mu\text{V}$$

consequences will be minimal. Although the above comments are aimed at 0 V and ground connections, because they are the ones most taken for granted, the nature of the problem is universal and applies to any conductor through which current flows. The power supply rail (or rails) is another special case where conductor impedance can create difficulties.

1.1.1 Grounding within one unit

In this context, “unit” can refer to a single circuit board or a group of boards and other wiring connected together within an enclosure such that you can identify a “local” ground point, for instance the point of entry of the mains earth. An example might be as shown in Figure 1.2. Let us say that printed circuit board (PCB) 1 contains input signal conditioning circuitry, PCB2 contains a microprocessor for signal processing and PCB3 contains high-current output drivers, such as for relays and for lamps. You may not place all these functions on separate boards, but the principles are easier to outline and understand if they are considered separately. The power supply unit (PSU) provides a low-voltage supply for the first two boards, and a higher-power supply for the output board. This is a fairly common system layout and Figure 1.2 will serve as a starting point to illustrate good and bad practice.

1.1.2 Chassis ground

First of all, note that connections are only made to the metal chassis or enclosure at one point. All wires that need to come to the chassis are brought to this point, which should be a metal stud dedicated to the purpose. Such connections are the mains safety earth (about which more later), the 0 V power rail, and any possible screening and filtering connections that may be required in the power supply itself, such as an electrostatic screen in the transformer. (The topic of power supply design is itself dealt with in much greater detail in Chapter 7.)

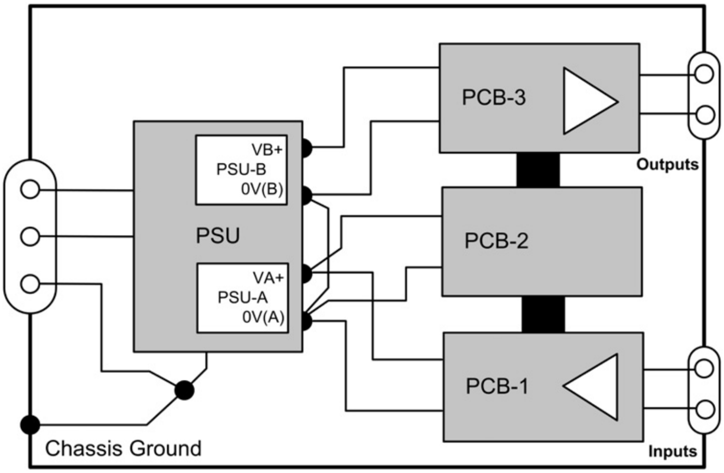

FIGURE 1.2 Typical intra-unit wiring scheme

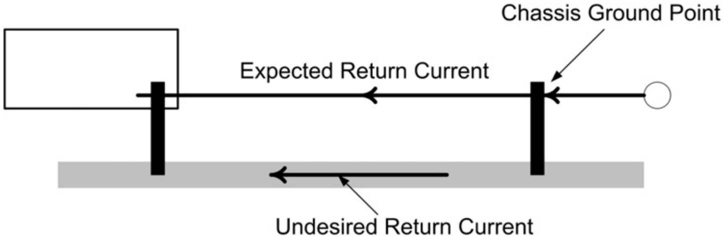

FIGURE 1.3 Return current paths with multiple ground points

The purpose of a single-point chassis ground is to prevent circulating currents in the chassis.[1] If multiple ground points are used, even if there is another return path for the current to take, a proportion of it will flow in the chassis (Figure 1.3); the proportion is determined by the ratio of impedances which depends on frequency. Such currents are very hard to predict and may be affected by changes in construction, so that they can give quite unexpected and annoying effects: it is not unknown for hours to be devoted to tracking down an oscillation or interference problem, only to find that it disappears when an inoffensive-looking screw is tightened against the chassis plate. Joints in the chassis are affected by corrosion, so that the unit performance may degrade with time, and they are affected by surface oxidation of the chassis material. If you use multi-point chassis grounding then it is necessary to be much more careful about the electrical construction of the chassis.

1.1.3 The conductivity of aluminum

Aluminum is used throughout the electronics industry as a light, strong and highly conductive chassis material – only silver, copper and gold have a higher conductivity. You would expect an aluminum chassis to exhibit a decently low bulk resistance, and so it does, and is very suitable as a conductive ground as a result. Unfortunately, another property of aluminum (which is useful in other contexts) is that it oxidizes very readily on its surface, to the extent that all real-life samples of aluminum are covered by a thin surface film of aluminum oxide (Al_2O_3). Aluminum oxide is an insulator. In fact, it is such a good insulator that anodized aluminum, on which a thick coating of oxide is deliberately grown by chemical treatment, is used for insulating washers on heatsinks.

The practical consequence of this quality of aluminum oxide is that the contact resistance of two sheets of aluminum joined together is unpredictably high. Actual electrical contact will only be made where the oxide film is breached. Therefore, whenever you want to maintain continuity through a chassis made of separate pieces of aluminum, you must ensure that the plates are tightly bonded together, preferably with welding or by fixings which incorporate shakeproof serrated washers to dig actively into the surface. The same applies to ground connection points. The best connection (since aluminum cannot easily be soldered) is a force-fit or welded stud (Figure 1.4), but if this is not available then a shakeproof serrated washer should be used underneath the nut which is in contact with the aluminum.

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[1] But, when RF shielding and/or a low-inductance ground is required, multiple ground points may be essential. This is covered in Chapter 8.

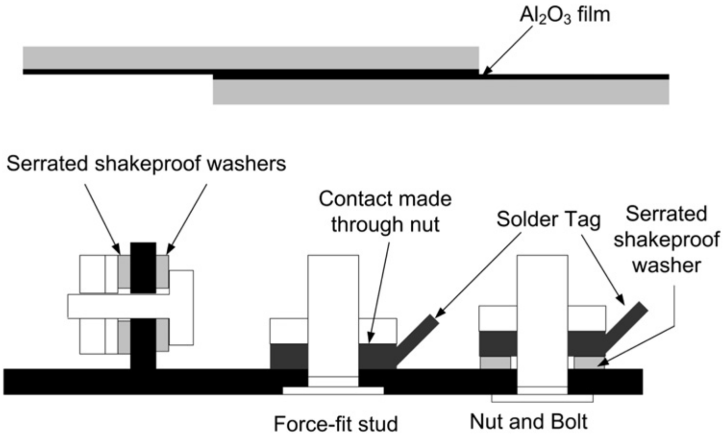

FIGURE 1.4 Electrical connections to aluminum

Other materials

Another common chassis material is cadmium- or tin-plated steel, which does not suffer from the oxidation problem. Mild steel has about three times the bulk resistance of aluminum so does not make such a good conductor, but it has better magnetic shielding properties and it is cheaper. Die-cast zinc is popular for its light weight and strength, and ease of creating complex shapes through the casting process; zinc's conductivity is 28% that of copper. Other metals, particularly silver-plated copper, can be used where the ultimate in conductivity is needed and cost is secondary, as in RF circuits. The advantage of silver oxide (which forms on the silver-plated surface) is that it is conductive and can be soldered through easily. Table 1.1 shows the conductivities and temperature coefficients of several metals.

1.1.4 Ground loops

Another reason for single-point chassis connection is that circulating chassis currents, when combined with other ground wiring, produce the so-called "ground loop", which is a fruitful source of low-frequency magnetically induced interference. A magnetic field can only induce a current to flow within a closed loop circuit. Magnetic fields are common around power transformers – not only the conventional 50 Hz mains type (60 Hz in the US), but also high-frequency switching transformers and inductors in switched-mode power supplies – and also other electromagnetic devices: contactors, solenoids and fans. Extraneous magnetic fields may also be present. The mechanism of ground-loop induction is shown in Figure 1.5.

Lenz's law tells us that the EMF induced in the loop is:

$$V = -10^{-8} \times A \times n \times dB/dt$$

where A is the area of the loop in cm^2, B is the flux density normal to it in microTesla (μT) assuming a uniform field, and n is the number of turns (n = 1 for a single-turn loop).

Table 1.1 Conductivity of Metals

Metal	**Relative conductivity (Cu = 1, at 20°C)**	**Temperature coefficient of resistance (/°C at 20°C)**
Aluminum (pure)	0.59	0.0039
Aluminum alloy:		
Soft-annealed	0.45–0.50	0.0039
Heat-treated	0.30–0.45	0.0039
Brass	0.28	0.002–0.007
Cadmium	0.19	0.0038
Copper:		
Hard-drawn	0.895	0.00382
Annealed	1.0	0.00393
Gold	0.65	0.0034
Iron:		
Pure	0.177	0.005
Cast	0.02–0.12	0.005
Lead	0.7	0.0039
Nichrome	0.0145	0.0004
Nickel	0.12–0.16	0.006
Silver	1.06	0.0038
Steel	0.03–0.15	0.004–0.005
Tin	0.13	0.0042
Tungsten	0.289	0.0045
Zinc	0.282	0.0037

As an example, take a 10 μT 50-Hz field as might be found near a reasonable-sized mains transformer, contactor or motor, acting at right angles through the plane of a 10-cm^2 loop that would be created by running a conductor 1 cm above a chassis for 10 cm and grounding it at both ends. The induced EMF is given by

$$\begin{aligned} V &= -10^{-8} \times 10 \times d/dt(10 \times \sin 2\pi \times 50 \times t) \\ &= -10^{-8} \times 10 \times 1000\pi \times \cos \omega t \\ &= 314\ \mu\text{V peak} \end{aligned}$$

Magnetic field induction is usually a low-frequency phenomenon (unless you happen to be very close to a high-power radio transmitter) and you can see from this example that in most circumstances the induced voltages are low. But in low-level applications, particularly audio and precision instrumentation, they are far from insignificant. If the input circuit includes a ground loop, the interference voltage is injected directly in series with the wanted signal and cannot then be separated from it. The cures are:

- open the loop by grounding only at one point;
- reduce the area of the loop (A in the equation above) by routing the offending wire(s) right next to the ground plane or chassis, or shortening it;

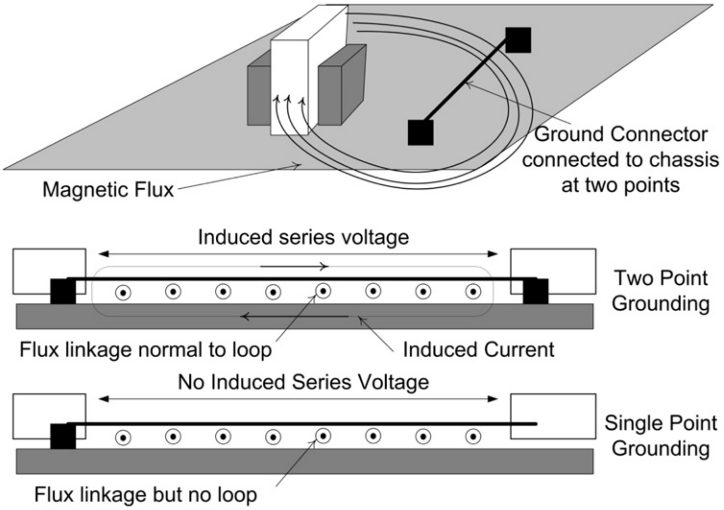

FIGURE 1.5 The ground loop

- reduce the flux normal to the loop by repositioning or reorienting the loop or the interfering source;
- reduce the interfering source, for instance by using a toroidal transformer.

1.1.5 Power supply returns

You will note from Figure 1.2 that the output power supply 0 V connection (0 V(B)) has been shown separately from 0 V(A), and linked only at the power supply itself. What happens if, say for reasons of economy in wiring, you don't follow this practice but instead link the 0 V rails together at PCB3 and PCB2, as shown in Figure 1.6?

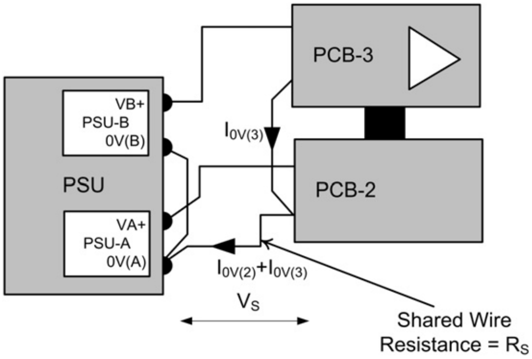

FIGURE 1.6 Common power supply return

The supply return currents I_{0V} from both PSUB/PCB3 and PSUA/PCB2 now share the same length of wire (or track, in a single-PCB system). This wire has a certain non-zero impedance, say for DC purposes it is R_S. In the original circuit this was only carrying $I_{0V(2)}$ and so the voltage developed across it was:

$$V_S = R_S \times I_{0V(2)}$$

but, in the economy circuit,

$$V_S = R_S \times (I_{0V(2)} + I_{0V(3)})$$

This voltage is in series with the supply voltages to both boards and hence effectively subtracts from them.

Putting some typical numbers into the equations,

$I_{0V(3)} = 1.2$ A with a VB+ of 24 V because it is a high-power output board,

$I_{0V(2)} = 50$ mA with a VA+ of 3.3 V because it is a microprocessor board with some CMOS logic on it.

Now assume that, for various reasons, the power supply is some distance remote from the boards and you have without thinking connected it with 2 m of 7/0.2 mm equipment wire, which will have a room temperature resistance of about 0.2 Ω. The voltage V_S will be

$$V_S = 0.2 \times (1.2 + 0.05) = 0.25\ \text{V}$$

which will drop the supply voltage at PCB2 to 3.05 V, less than the lower limit of operation for 3.3 V logic, *before* allowing for supply voltage tolerances and other voltage drops. One wrong wiring connection can make your circuit operation borderline! Of course, the 0.25 V is also subtracted from the 24 V supply, but a reduction of about 1% on this supply is unlikely to affect operation.

Varying loads

If the 1.2 A load on PCB3 is varying – say several high-current relays may be switched at different times, ranging from all off to all on – then the V_S drop at PCB2 would also vary. This is very often worse than a static voltage drop because it introduces noise on the 0 V line. The effects of this include unreliable processor operation, variable set threshold voltage levels and odd feedback effects such as chattering relays or, in audio circuits, low-frequency "motor-boating" oscillation.

For comparison, look at the same figures but applied to Figure 1.2, with separate 0 V return wires. Now there are two voltage drops to consider: $V_{S(A)}$ for the 3.3-V supply and $V_{S(B)}$ for the 24-V supply. $V_{S(B)}$ is 1.2 A times 0.2 Ω, substantially the same (0.24 V) as before, but it is only subtracted from the 24-V supply. $V_{S(A)}$ is now 50 mA times 0.2 Ω or 10 mV, which is the only 0 V drop on the 3.3-V supply to PCB2 and is negligible.

The rule is: always separate power supply returns so that load currents for each supply flow in separate conductors (Figure 1.7).

Note that this rule is easiest to apply if different power supplies have different 0 V connections (as in Figure 1.2) but should also be applied if a common 0 V is used, as shown above. The extra investment in wiring is just about always worth it for peace of mind!

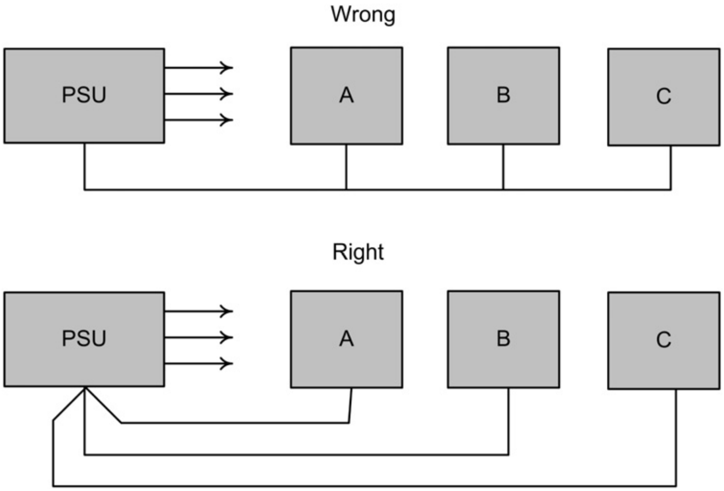

FIGURE 1.7 Ways to connect power supply returns

Power rail feed

The rule also applies to the power rail feed as well as to its return, and in fact to any connection where current is being shared between several circuits. Say the high-power load on PCB3 was also being fed from the +5 V supply VA+, then the preferred method of connection is two separate feeds (Figure 1.8).

The reasons are the same as for the 0 V return: with a single feed wire, a common voltage drop appears in series with the supply voltage, injected this time in the supply rail rather than the 0 V rail. Fault symptoms are similar. Of course, the example above is somewhat artificial in that you would normally use a rather more suitable size of wire for the current expected. High currents flowing through long wires demand a low-resistance and hence a thick conductor is required. If you are expecting a significant voltage drop then you will take the trouble to calculate it for a given wire diameter, length and current. See Table 1.3 on page 24 for a guide to the current-carrying abilities of common wires. The point of the previous examples is that voltage drops have a habit of cropping up when you are *not* expecting them.

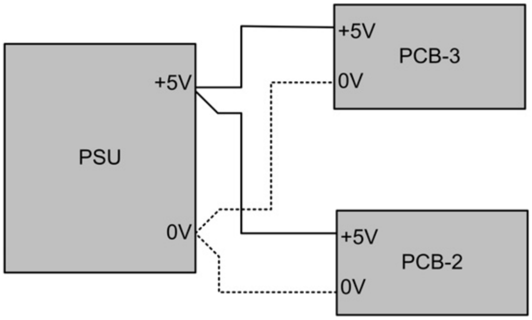

FIGURE 1.8 Separate power supply rail feeds

Conductor impedance

Note that the previous examples, and those on the next few pages, tacitly assume for simplicity that the wire impedance is resistive only. In fact, real wire has inductance as well as resistance and this comes into effect as soon as the wire is carrying AC, increasing in significance as the frequency is raised. A one-meter length of 16/0.2 equipment wire has a resistance of 38 mΩ and a self-inductance of 1.5 μH. At 4 A DC the voltage drop across it will be 152 mV. An AC current with a rate of change of 4 A/μs will generate 6 V across it. Note the difference! The later discussion of wire types includes a closer look at inductance.

1.1.6 Input signal ground

Figure 1.2 shows the input signal connections being taken directly to PCB1 and not grounded outside of the PCB. To expand on this, the preferred scheme for two-wire single-ended input connections is to take the ground return directly to the reference point of the input amplifier, as shown in Figure 1.9(a).

The reference point on a single-ended input is not always easy to find: look for the point from which the input voltage must be developed in order for the amplifier gain to act on it alone. In this way, no extra signals are introduced in series with the wanted signal by means of a common impedance. In each of the examples in Figure 1.9 of bad input wiring, getting progressively worse from (b) to (d), the impedance X–X acts as a source of unwanted input signal due to the other currents flowing in it as well as the input current.

Connection to 0 V elsewhere on the PCB

Insufficient control over pc layout is the most usual cause of arrangement (b), especially if auto-routing layout software is used. Most CAD layout software assumes that the 0 V rail is a single node and feels itself free to make connections to it at any point along the track. To overcome this, either specify the input return point as a separate node and connect it later, or edit the final layout as required. Manual layout is capable of exactly the same mistake, although in this case it is due to lack of communication between designer and layout draughtsman.

Connection to 0 V within the unit

Arrangement (c) is quite often encountered if one pole of the input connector naturally makes contact with the metal case, such as happens with the standard BNC coaxial connector, or if for reasons of connector economy a common ground conductor is shared between multiple input, output or control signals that are distributed among different boards. With sensitive input signals, the latter is false economy; and if you have to use a BNC-type connector, you can get versions with insulating washers, or mount it on an insulating sub-panel in a hole in the metal enclosure. Incidentally, taking a coax lead internally from an uninsulated BNC socket to the PCB, with the coax outer connected both to the BNC shell and the PCB 0V, will introduce a ground loop (see Section 1.1.4) unless it is the only path for ground currents to take. But at radio frequencies, this effect is countered by the ability of coax cable to concentrate the signal and return currents within the cable, so that the ground loop is only a problem at low frequencies.

External ground connection

Despite being the most horrific input grounding scheme imaginable, arrangement (d) is unfortunately not rare. Now, not only are noise signals internal to the unit coupled into the signal path, but also all

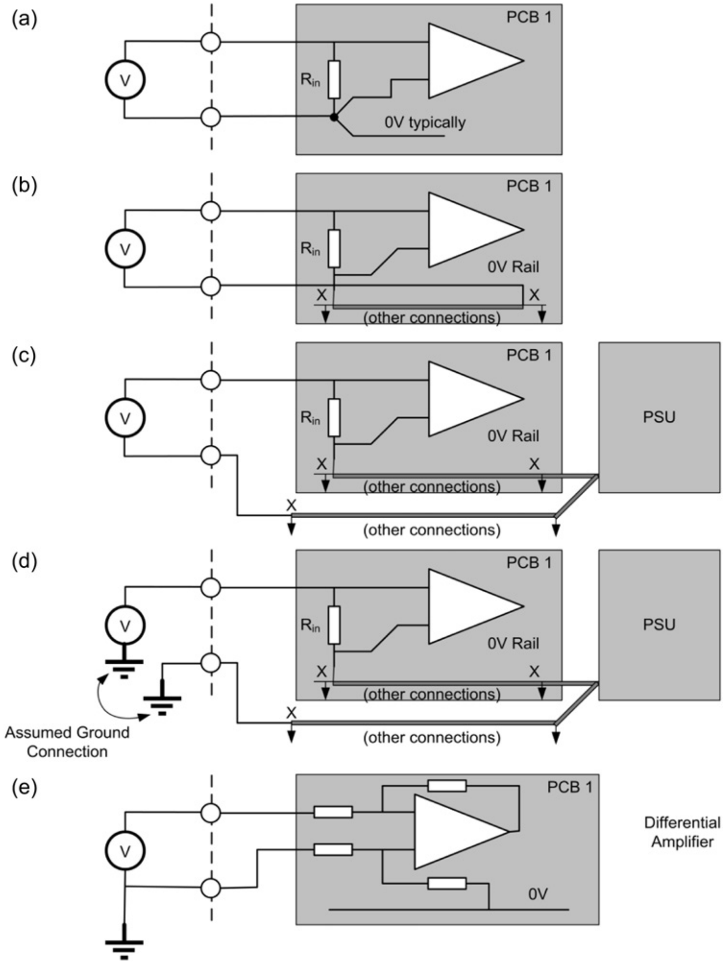

FIGURE 1.9 Input signal grounding

manner of external ground noise is included. Local earth differences of up to 50 V at mains frequency can exist at particularly bad locations such as power stations, and differences of several volts are more common. The only conceivable reason to use this layout is if the input signal is already firmly tied to a remote ground outside the unit, and if this is the case it is far better to use a differential amplifier as in Figure 1.9(e), which is often the only workable solution for low-level signals and is in any case only a logical development of the correct approach for single-ended signals (a). If for some reason you are unable to take a ground return connection from the input signal, you will be stuck with ground-injected noise.

All of the schemes of Figure 1.9(b) to (d) will work perfectly happily if the desired input signal is several orders of magnitude greater than the ground-injected interference, and this is frequently the case, which is how they came to be common practice in the first place. If there are good practical reasons for adopting them (for instance, connector or wiring cost restrictions) and you can be sure that interference levels will not be a problem, then do so. But you will need to have control over all possible connection paths before you can be sure that problems won't arise in the field.

1.1.7 Output signal ground

Similar precautions need to be taken with output signals, for the reverse reason. Inputs respond unfavorably to external interference, whereas outputs are the cause of interference. Usually in an electronic circuit there is some form of power amplification involved between input and output, so that an output will operate at a higher current level than an input, and there is therefore the possibility of unwanted feedback.

The classical problem of output-to-input ground coupling is where both input and output share a common impedance, in the same way as the power rail common impedances discussed earlier. In this case the output current is made to circulate through the same conductor as connects the input signal return (Figure 1.10(a)).

A tailor-made feedback mechanism has been inserted into this circuit, by means of R_S. The input voltage at the amplifier terminals is supposed to be V_{in}, but actually it is:

$$V_{in}{}' = V_{in} - (I_{out} \times R_S)$$

Redrawing the circuit to reference everything to the amplifier ground terminals (Figure 1.10(b)) shows this more clearly. When we work out the gain of this circuit, it turns out to be:

$$V_{out}/V_{in} = A/(1 + [A \times R_S/(R_L + R_S)])$$

which describes a circuit that will oscillate if the term $[A \times R_S/(R_L + R_S)]$ is more negative than -1. In other words, for an inverting amplifier, the ratio of load impedance to common impedance must be less than the gain, to avoid instability. Even if the circuit remains stable, the extra coupling due to R_S upsets the expected response. Remember also that all the above terms vary with frequency, usually in a complex fashion, so that at high frequencies the response can be unpredictable. Note that although this has been presented in terms of an analog system (such as an audio amplifier), any system in which there is input–output gain will be similarly affected. This can apply equally to a digital system with an analog input and digital outputs which are controlled by it.

Avoiding the common impedance

The preferable solution is to avoid the common impedance altogether by careful layout of input and output grounds. We have already looked at input grounds, and the grounding scheme for outputs is essentially similar: take the output ground return directly to the point from which output current is sourced, with no other connection (or at least, no other susceptible connection) in between. Normally, the output current comes from the power supply so the best solution is to take the return directly back to the supply. Thus the layout of PCB3 in Figure 1.2 should have a separate ground track for the high-current output as in Figure 1.11(a), or the high-current output terminal could be returned directly to the power supply, bypassing PCB3 (b).

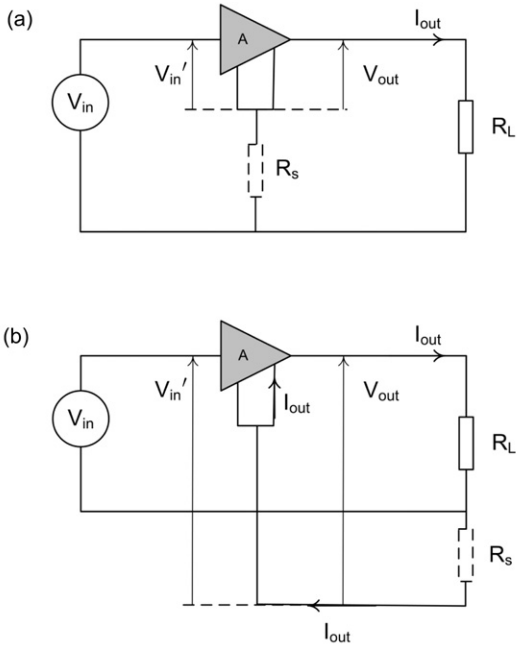

FIGURE 1.10 Output to input coupling

If PCB3 contains only circuits which will not be susceptible to the voltage developed across R_S, then the first solution is acceptable. The important point is to decide in advance where your return currents will flow and ensure that they do not affect the operation of the rest of the circuits. This entails knowing the AC and DC impedance of any common connections, the magnitude and bandwidth of the output currents and the susceptibility of the potentially affected circuits.

1.1.8 Inter-board interface signals

There is one class of signals we have not yet covered, and that is those signals which pass within the unit from one board to another. Typically these are digital control signals or analog levels which have already been processed, so are not low-level enough to be susceptible to ground noise and are not high-current enough to generate significant quantities of it. To be thorough in your consideration of ground return paths, these signals should not be left out: the question is, what to do about them?

Often the answer is nothing. If no ground return is included specifically for inter-board signals then signal return current must flow around the power supply connections and therefore the interface will suffer all the ground-injected noise V_n that is present along these lines (Figure 1.12). But, if your grounding scheme is well thought out, this may well not be enough to affect the operation of the interface. For instance, 100 mV of noise injected in series with a CMOS logic interface which has a noise margin of 1 V will have no direct effect. Or, AC noise injection onto a DC analog signal which is well-filtered at the interface input will be tolerable.

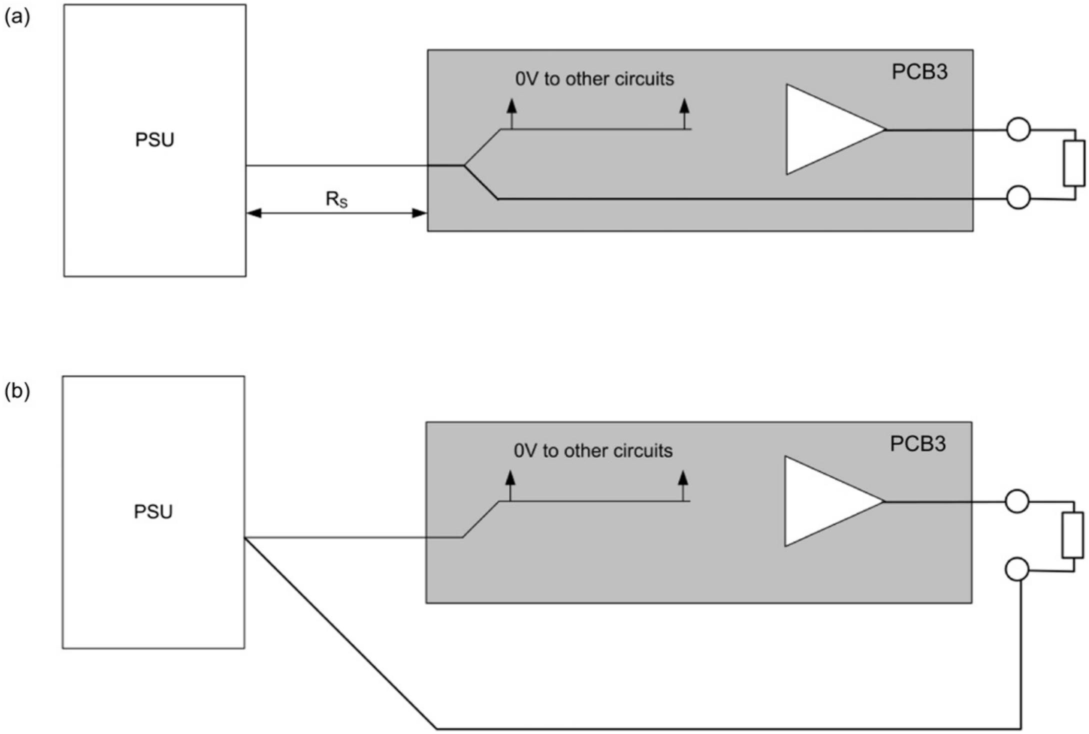

FIGURE 1.11 Output signal returns

Partitioning the signal return

There will be occasions when taking the long-distance ground return route is not good enough for your interface. Typically these are:

- where high-speed digital signals are communicated, and the ground return path has too much inductance, resulting in ringing on the signal transitions;
- when interfacing precision analog signals which cannot stand the injected noise or low-voltage DC differentials.

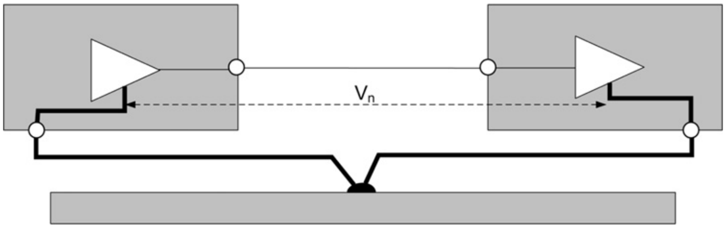

FIGURE 1.12 Inter-board ground noise

If you solve these headaches by taking a local inter-board ground connection for the signal of interest, you run the risk of providing an alternative path for power supply return currents, which nullifies the purpose of the local ground connection. A fraction of the power return current will flow in the local link (Figure 1.13), the proportion depending on the relative impedances, and you will be back where you started.

If you really need the local signal return, but are in trouble with ground return currents, there are two options to pursue:

- Separate the ground return (Figure 1.14) for the input side of the interface from the rest of the ground on that PCB. This has the effect of moving the ground noise injection point inboard, after the input buffer, which may be all that you need. A development of this scheme is to include a "stopper" resistor of a few ohms in the gap X–X. This prevents DC ground current flow because its impedance is high relative to that of the correct ground path, but it effectively ties the input buffer to its parent ground at high frequencies and prevents it from floating if the inter-board link is disconnected.
- Use differential connections at the interface. The signal currents are now balanced and do not require a ground return; any ground noise is injected in common mode and is cancelled out by the input buffer. This technique is common where high-speed or low-level signals have to be communicated some distance, but it is applicable at the inter-board level as well. It is of course more expensive than typical single-ended interfaces since it needs dedicated buffer drivers and receivers.

1.1.9 Star-point grounding

One technique that can be used as a circuit discipline is to choose one point in the circuit and to take all ground returns to this point. This is then known as the "star point". Figure 1.2 shows a limited use of this technique in connecting together chassis, mains earth, power supply ground and 0 V returns to one point. It can also be used as a local sub-ground point on printed circuit layouts.

When comparatively few connections need to be made this is a useful and elegant trick, especially as it offers a common reference point for circuit measurements. It can be used as a reference for power supply voltage sensing, in conjunction with a similar star point for the output voltage (see Figure 1.2 again). It becomes progressively messier as more connections are brought to it, and should not substitute for a thorough analysis of the anticipated ground current return paths.

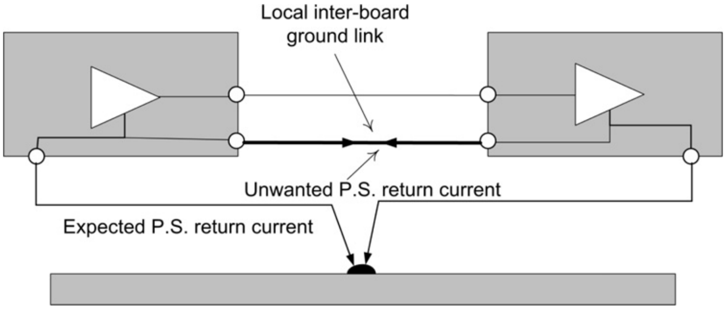

FIGURE 1.13 Power supply return currents through inter-board links

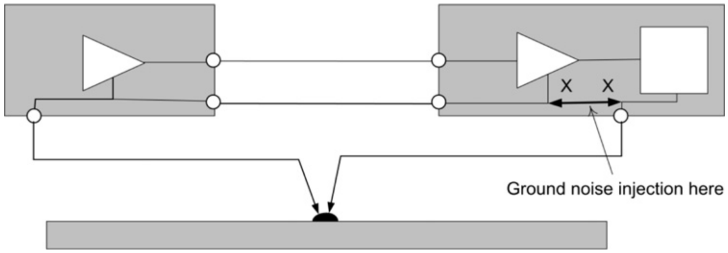

FIGURE 1.14 Separating the ground returns

1.1.10 Ground connections between units

Much of the theory about grounding techniques tends to break down when confronted with the prospect of several interconnected units. This is because the designer often has either no control over the way in which units are installed, or is forced by safety-related or other installation practices to cope with a situation which is hostile to good grounding practice.

The classic situation is where two mains-powered units are connected by one (or more) signal cable (Figure 1.15). This is the easiest situation to explain and visualize; actual set-ups may be complicated by having several units to contend with, or different and contradictory ground regimes, or by extra mechanical bonding arrangements.

This configuration is exactly analogous to that of Figure 1.12. Ground noise, represented by V_n, is coupled through the mains earth conductors and is unpredictable and uncontrollable. If the two units are plugged in to the same mains outlet, it may be very small, though never zero, as some noise is induced simply by the proximity of the live and neutral conductors in the equipment mains cable. But this configuration cannot be prescribed: it will be possible to use outlets some distance apart, or even on different distribution rings, in which case the ground connection path could be lengthy and could include several noise injection sources. Absolute values of injected noise can vary from less than a millivolt RMS in very quiet locations to the several volts, or even tens of volts, as mentioned in Section 1.1.6. This noise effectively appears in series with the signal connection.

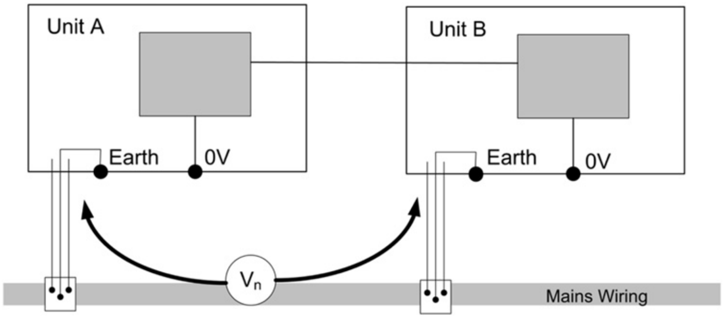

FIGURE 1.15 Inter-unit ground connection via the mains

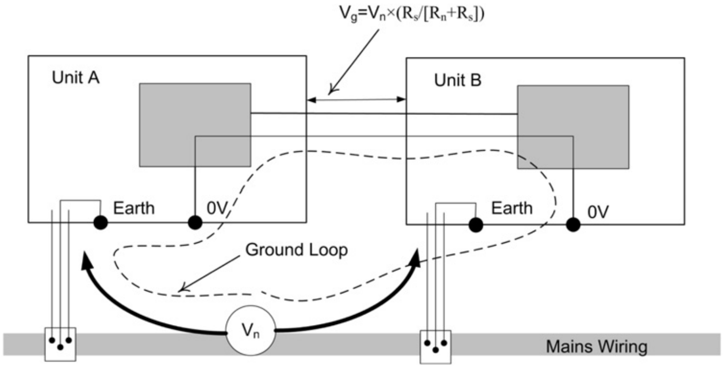

FIGURE 1.16 Ground loop via signal and mains earths

In order to tie the signal grounds in each unit together you would normally run a ground return line along with the signal in the same cable, but then:

- noise currents can now flow in the signal ground, so it is essential that the impedance of the ground return (R_S) is much less than the noise source impedance (R_n) – usually but not invariably the case – otherwise the ground-injected noise will not be reduced;
- you have created a ground loop (Figure 1.16, and compare this with Section 1.1.4) which by its nature is likely to be both large and variable in area, and to intersect various magnetic field sources, so that induced ground currents become a real hazard.

Breaking the ground link

If the susceptibility of the signal circuit is such that the expected environmental noise could affect it, then you have a number of possible design options:

- Float one or other unit (disconnect its mains ground connection), which breaks the ground loop at the mains lead. This is already done for you if it is battery-powered and in fact this is one good reason for using battery-powered instruments. On safety-class I (earthed) mains-powered equipment, doing this is not an option because it violates the safety protection.
- Transmit your signal information via a differential link, as recommended for inter-board signals earlier. Although a ground return is not necessary for the signal, it is advisable to include one to guard against too large a voltage differential between the units. Noise signals are now injected in common-mode relative to the wanted signal and so will be attenuated by the input circuit's common mode rejection, up to the operating limit of the circuit, which is usually several volts.
- Electrically isolate the interface. This entails breaking the direct electrical connection altogether and transmitting the signal by other means, for instance a transformer, opto-coupler or fiber optic link. This allows the units to communicate in the presence of several hundred volts or more of noise, depending on the voltage rating of the isolation; alternatively it is useful for communicating low-level AC signals in the presence of relatively moderate amounts of noise that cannot be eliminated by other means.

1.1.11 Shielding

Some mention must be made here of the techniques of shielding inter-unit cables, even though this is more properly the subject of Chapter 8. Shielded cable is used to protect signal wires from noise pickup, or to prevent power or signal wires from radiating noise. This apparently simple function is not so simple to apply in practice. The characteristics of shielded cable are discussed later (see Section 1.2.4); here we shall look at how to apply it.

At which end of a cable do you connect the shield, and to what? There is no one correct answer, because it depends on the application. If the cable is used to connect two units which are both contained within screened enclosures to keep out or keep in RF energy, then the cable shield has to be regarded as an extension of the enclosures and it must be connected to the screening at both ends via a low-inductance connection, preferably the connector screen itself (Figure 1.17). This is a classic application of EMC principles and is discussed more fully in Sections 8.5 and 8.7. Note that if both of the unit enclosures are themselves separately grounded then you have formed a ground loop (again). Because ground loops are a magnetic coupling hazard, and because magnetic coupling diminishes in importance at higher frequencies, this is often not a problem when the purpose of the screen is to reduce HF noise. The difficulty arises if you are screening both against high and low frequencies, because at low frequencies you should ground the shield at one end only, and in these cases you may have to take the expensive option of using double-shielded cable.

The shield should not be used to carry signal return currents unless it is at RF and you are using coaxial cable. Noise currents induced in it will add to the signal, nullifying the effect of the shield. Typically, you will use a shielded pair to carry high-impedance low-level input signals which would be susceptible to capacitive pickup. (A cable shield will *not* be effective against magnetic pickup, for which the best solution is twisted pair.)

Which end to ground for LF shielding

If the input source is floating, then the shield can be grounded at the amplifier input. A source with a floating screen around it can have this screen connected to the cable shield. But, if the source screen is itself grounded, you will create a ground loop with the cable shield, which is undesirable: ground loop current induced in the shield will couple into the signal conductors. One or other of the cable

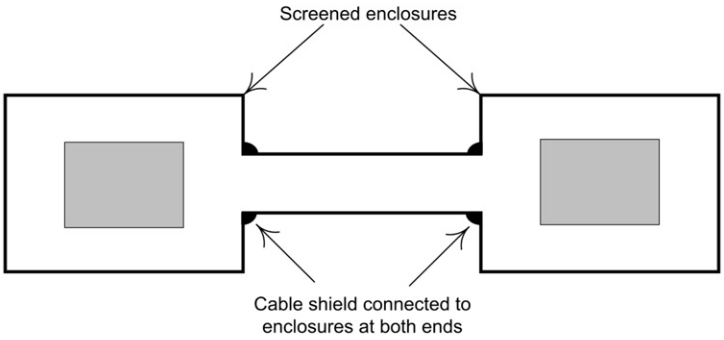

FIGURE 1.17 RF Cable shield connections

shield ends should be left floating, depending on the relative amount of unavoidable capacitive coupling to ground (C_c) that exists at either end. If you have the choice, usually it is the source end (which may be a transducer or sensor) that has the lower coupling capacitance so this end should be floated.

If the source is single-ended and grounded, then the cable shield should be grounded at the source and either left floating at the (differential) input end or connected through a choke or low-value resistor to the amplifier ground. This will preserve DC and low-frequency continuity while blocking the flow of large induced high-frequency currents along the shield. The shield should not be grounded at the opposite end to the signal. Figure 1.18 shows the options.

Electrostatic screening

When you are using shielded cable to prevent electrostatic radiation from output or inter-unit lines, ground loop induction is usually not a problem because the signals are not susceptible, and the cable shield is best connected to ground at both ends. The important point is that each conductor has a distributed (and measurable) capacitance to the shield, so that currents on the shield will flow as long as there are AC signals propagating within it. See Figure 1.19. These shield currents must be provided with a low-impedance ground return path so that the shield voltages do not become substantial. The same applies in reverse when you consider coupling of noise induced on the shield into the conductors.

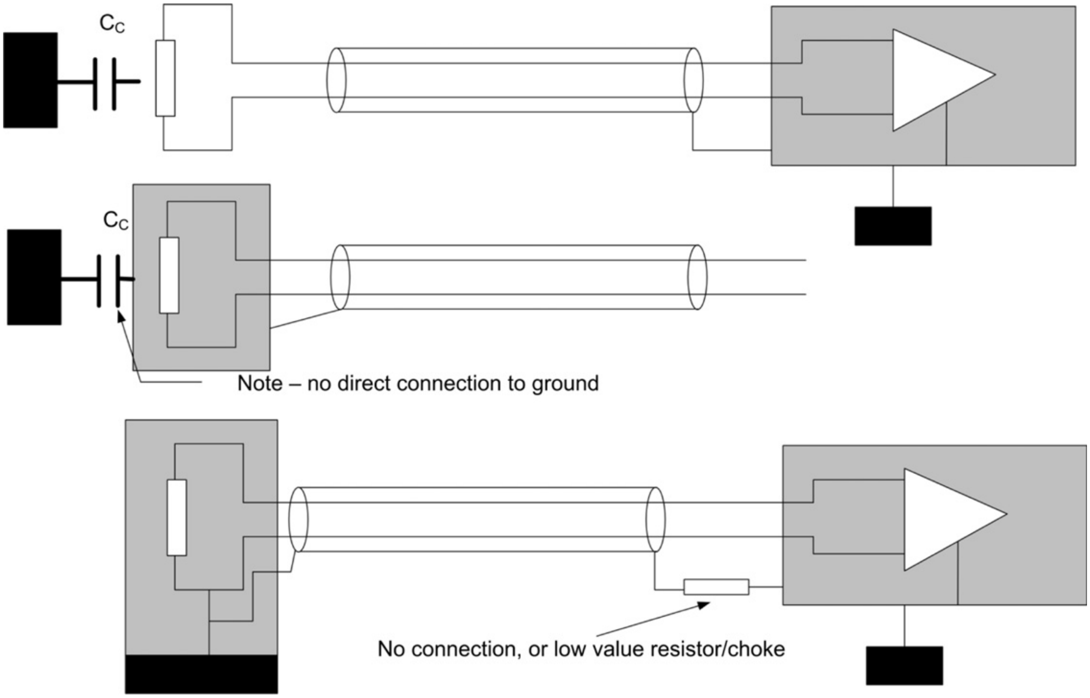

FIGURE 1.18 Cable shield connection options

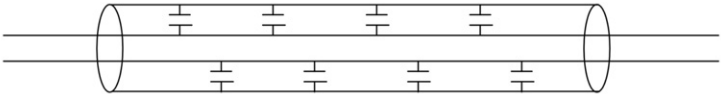

FIGURE 1.19 Conductor to shield coupling capacitance

Surface transfer impedance

At high frequencies, the notion of surface transfer impedance becomes useful as a measure of shielding effectiveness. This is the ratio of voltage developed between the inner and outer conductors of shielded cable due to interference current flowing in the shield, expressed in milliohms per unit length. It should not be confused with characteristic impedance, with which it has no connection. A typical single braid screen will be 10 milliohms/m or so below 1 MHz, rising at a rate of 20 dB/decade with increasing frequency. The common aluminum/Mylar foil screens are around 20 dB worse. Unhappily, surface transfer impedance is rarely specified by cable manufacturers.

1.1.12 The safety earth

A brief word is in order about the need to ensure a mains earth connection, since it is obvious from the preceding discussion that this requirement is frequently at odds with anti-interference grounding practice. Most countries now have electrical standards which require that equipment powered from dangerous voltages should have a means of protecting the user from the consequences of component failure. The main hazard is deemed to be inadvertent connection of the live mains voltage to parts of the equipment with which the user could come into contact directly, such as a metal case or a ground terminal.

Imagine that the fault is such that it makes a short circuit between live and case, as shown in Figure 1.20. These are normally isolated and if no earth connection is made the equipment will continue to function normally – but the user will be threatened with a lethal shock hazard without knowing it. If the safety earth conductor is connected then the protective mains fuse will blow when the fault occurs, preventing the hazard and alerting the user to the fault.

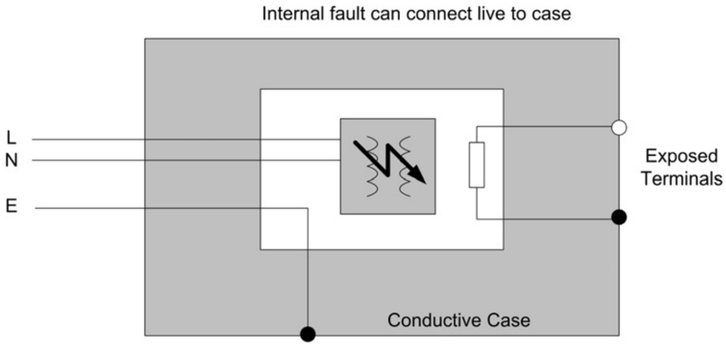

FIGURE 1.20 The need for a safety earth