4

Avoid the Worst Thinking Traps

Engineering should be about doing things right. A system such as a bridge, telephone, or traffic light should be designed to function properly over a certain lifetime. It should satisfy its intended purpose. The same holds for a formal technical document meant to describe an engineering system, communicate an engineering procedure, or develop an engineering idea.

This book addresses the combination of thinking and writing skills necessary to produce effective formal documents. As engineers, we are not merely required to think; we must also avoid major pitfalls in our thinking. We ignore this responsibility at our own peril (and often at the peril of others).

Example. Tom maintained a high grade-point average in college by always demanding detailed instructions and following them to the letter. As a newly-hired chemical engineer, however, he is required to think on his own in virtually every situation. Tom is somewhat overconfident about the integrity of his thought processes. Today he must decide how a batch of hydrofluoric acid (HF) should be stored in the company's new lab room. He thinks to himself,

> Acids are stored in glass containers. HF is an acid, so it should go in a big glass jar.

Tom fails to verify that HF shares the properties of the other acids he's thinking of. In fact, while it's true that acids are commonly stored in glass containers, HF is used to etch glass. It obviously cannot be stored in a glass container. Tom causes a chemical spill in the company's new lab, and hazardous material and cleanup crews must be summoned at great expense. Tom learns that his high grade-point average holds little value in this situation; he soon finds himself seeking a new job.

Tom has committed a blunder called the Fallacy of Accident. We'll return to it later, but for now it's obvious that Tom should have done his homework rather than basing his decision on an assumption. Avoidance of common fallacious patterns is the main thrust of the present chapter.

4.1 Claims vs. Facts

In Chapter 2 we mentioned the role of persuasion in certain types of engineering documents. We cannot deny that a persuasive component is sometimes essential. A substantial portion of a patent application consists of claims that specify the essence of the invention and allow clear understanding of what will infringe the patent post issue. Although some portion of the claims consists of factual material, a main purpose is to persuade the examiner as to the novelty of the invention. Indeed, the purpose of even the most technical argument (such as a mathematical proof) is to persuade ourselves and others that the conclusion of the argument holds. For this reason, in this chapter we will emphasize the notion of *claim* instead of the notion of *fact*.

Many of the things written in technical documents are, from our present viewpoint, *technical claims*.

Example. These are technical claims:

All acids are dangerous.
The optimal value is $x_0 = 1.45$.
Some antennas are omnidirectional.

These are not technical claims:

Let $y_1 = 19$.
The purpose of this chapter is to introduce the gamma function.
We would like to thank Dr. S.P. Smith for his valuable guidance.

Indeed, it would be irrational to dispute any of them. The second, for instance, merely states an author's intention.

The attributes of a good technical claim include

1. clarity — the claim must be understandable;
2. verifiability — the claim must be supportable.

Clarity is greatly supported by grammatical structure, the topic of Chapter 5. For example, patent attorneys use a very specific syntax with strict grammatical rules to prevent the misunderstanding of claims. In this chapter we deal with issues related to verifiability. Along the way, we will touch on some elements of logic and heuristic reasoning. Our treatment is informal and we make no attempt to compete with textbooks on logic. Our main goal is to save you from writing things that are illogical or otherwise outrageous.

4.2 Logical Fallacies

First, we recall that *deductive argument* moves from accepted truths to their logical consequences. *Inductive argument*, on the other hand, attempts to move from specific observations to general consequences. These are the two basic modes of reasoning in Western thought. In this section we examine some elementary deductive fallacies that may appear in careless writing. Avoid them at all costs!

Syllogistic Fallacies

We begin with the famous argument

All men are mortal.
Socrates is a man.
Therefore, Socrates is mortal.

This is an example of a *categorical syllogism*. It consists of two *premises* (or *assumptions*) and a *conclusion*. The argument is valid not because the conclusion holds, but because the truth of the conclusion must follow from that of the two premises. Any argument of the general form

All S are P.
x is an S. ✓ valid
Therefore, x is P.

is valid for the same reason. In Figure 4.1 we use diagrams to clarify the situation. Although these are not as rigorous as the *Euler* and *Venn diagrams* that appear in logic books, they will suffice for our purposes.

We must be on the lookout for the categorical syllogism. Such an argument may be shortened by leaving one of the premises unstated.

Example. Consider the syllogism

All machines eventually fail.
An automobile is a machine.
Therefore, an automobile will eventually fail.

Leaving the second premise understood, we could write

Machines eventually fail, hence an automobile will eventually fail.

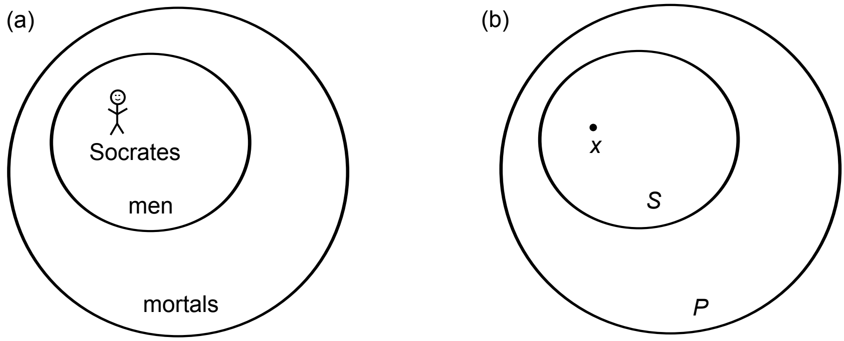

FIGURE 4.1
A categorical syllogism. (a) Concrete case. Socrates falls within the set of all men, and the set of all men is a subset of the set of all mortals. Hence Socrates must be a mortal. (b) Abstract case. The point x falls within the set S, which is itself a subset of a set P. Clearly x must fall within P.

Leaving the first premise understood, we would write

> An automobile is a machine, so it will eventually fail.

Both of these are still considered syllogisms.

So far, so good. However, we must also guard against *syllogistic fallacies.* These arguments masquerade as valid syllogisms but fail the basic test mentioned above, i.e., that the truth of the conclusion *must* (not *may*) follow from the truth of the premises.

Example.

> All bottles containing hydrochloric acid must be marked "Corrosive." This bottle is marked "Corrosive." It must contain hydrochloric acid.

The general form in this case is

All H is C.
y is C. $\times$ invalid
Therefore, y is H.

The invalid nature of this argument is clear from Figure 4.2(a). The point y shown in the figure is an *invalidating counterexample*, and it takes only one of these to prove an argument invalid.

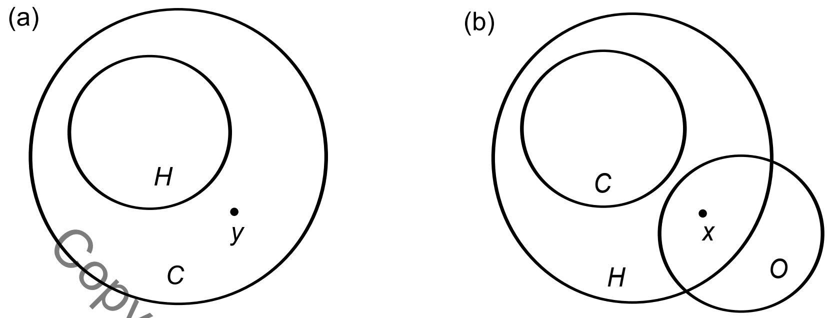

FIGURE 4.2
Two invalid syllogisms. (a) Everything that has the attribute H also has the attribute C. However, the additional assumption that y has the attribute C does not imply that it *must* have the attribute H. (b) The assumption that O and C are disjoint does not imply that O and H are disjoint. An element x can belong to both O and H.

Example.

All chemicals in our lab are marked "Hazardous." No chemicals in our lab are organic. So no organic chemicals in our lab are marked "Hazardous."

The general form in this case is

All C is H.
No C is O. $\times$ invalid
Therefore, no O is H.

See Figure 4.2(b); the counterexample x shows that this argument is also fallacious.

These examples show that we must consider the very structure of an argument, not just the truth of the individual statements it contains. They also show how easy it is to fall into the trap of a fallacious argument.

In deductive logic, an argument is said to be *valid* if its conclusion must be true whenever its premises are true (or, as logicians say, the conjunction of the premises implies the inclusion). If, in addition, the premises are actually true, the argument is said to be *sound*.

Example. The argument

> All engineers are wealthy. Jo is an engineer. Hence Jo is wealthy.

is valid. It is not sound, however, because the first premise is false.

Example. Here is a sound argument:

> All positive real numbers are nonnegative. Ten is a positive real number. So the number ten is nonnegative.

The argument form is valid and both premises are true.

Needless to say, engineers should be advancing sound arguments.

Arguments Involving Conditional Statements

Before considering additional valid argument forms, we must modify our notation a bit. From now on, unless otherwise stated, uppercase letters such as P and Q will denote *statements* rather than classes of objects. So P could be

> the area of a square having side length L equals L^2

which is a true statement, and Q could be

> -4.2 is a positive integer

which is a false statement. A compound statement of the form

> If P, then Q.

is a *conditional statement*; the statement P is its *antecedent* and Q is its *consequent*. Take a moment to memorize these terms; they are standard and will occur repeatedly in the next few pages.

Example. Consider the conditional statement

> If I am a lawyer, then I can understand legal contracts.

Let's break it down:

$$\text{If } \underbrace{\text{I am a lawyer}}_{\text{antecedent, } P}\text{, then } \underbrace{\text{I can understand legal contracts}}_{\text{consequent, } Q}.$$

Note that we are not free to interchange the antecedent and consequent of a conditional statement without a (possibly drastic) change in meaning.

Example. The statement

> If I can understand legal contracts, then I am a lawyer.

is clearly false; many engineers can understand legal contracts. This statement is called the *converse* of the statement in the preceding example.

In Chapter 7, we will have more to say about the converse of a conditional statement; we'll also cover two related statements called the *inverse* and *contrapositive*. Of these, only the contrapositive is equivalent to the original conditional. We now examine some argument forms involving conditional statements. Please don't be discouraged by their technical sounding names. Arguments of these forms are recognizable in all engineering discourse.

Modus Ponens, or Affirming the Antecedent

The pattern

> If P, then Q.
> P. ✓ valid
> Therefore, Q.

is a standard argument form called *modus ponens*. Since the antecedent of the conditional in the first premise is affirmed by the second premise, the form is also called *affirming the antecedent*.

Example. The argument

> If our proposal contains errors, we won't receive funding. Our proposal does contain errors. So we won't receive funding.

takes the form of modus ponens. It is a valid argument.

Modus Tollens, or Denying the Consequent

The following pattern is a standard argument form called *modus tollens*. By *not-Q*, we mean the statement called the *negation of Q*.

If P, then Q.
Not-Q. ✓ valid
Therefore, not-P.

In English we can negate a statement by appending *It is false that* to the start of it, although this may not yield the most concise or graceful formulation.

Example. The statement

> All real numbers are positive.

is false. Its negation can be phrased in any of the following ways:

> It is false that all real numbers are positive.
> Not all real numbers are positive.
> Some real numbers are not positive.
> There is at least one real number that is not positive.

The negation of a false statement is true, and the negation of a true statement is false. Let's get back to modus tollens. Since the consequent of the conditional in the first premise is denied by the second premise, the form is also called *denying the consequent*.

Example. The argument

> If the machine works properly, its output exceeds two units per hour. Its output does not exceed two units per hour. So the machine does not work properly.

takes the form of modus tollens. It is a valid argument.

An Argument Form with Two Conditional Premises

Here's another standard reasoning pattern, this time with conditional statements for both premises.

If P, then Q.
If Q, then R. ✓ valid
Therefore, if P then R.

Example.

> If V_0 exceeds 10 V, the output current will exceed 1 mA. If the output current exceeds 1 mA, the system will fail. We conclude that if V_0 exceeds 10 V, the system will fail.

Fallacies Involving Conditional Statements

What can go wrong with arguments containing conditional statements? There are two famous fallacies to guard against. The first is called *affirming the consequent*.

Example. The argument

> If the voltage is high, the current is low. The current is low. Therefore the voltage is high.

is *not* modus ponens. The antecedent of the conditional ("the voltage is high") is not affirmed in the second premise; rather, the consequent ("the current is low") is affirmed. This argument is invalid.

In general, an argument of the following form is fallacious.

> If P, then Q.
> Q. $\times$ invalid
> Therefore, P.

Again, this is called affirming the consequent. Let's proceed to the second fallacious form.

Example. The argument

> If our design is the best, we will win the competition. Our design is not the best. Therefore we will not win the competition.

is *not* modus tollens. The consequent of the conditional ("we will win the competition") is not denied; rather, the antecedent ("our design is the best") is denied. This argument is invalid.

In general, an argument of the following form is fallacious.

If P, then Q.
Not-P. × invalid
Therefore, not-Q.

This is called *denying the antecedent*.

The Disjunctive Syllogism

Another valid argument form, commonly seen, is the *disjunctive syllogism*. The pattern is

P or Q.
Not-P. ✓ valid
Therefore, Q.

The first premise guarantees that at least one of the statements P and Q must hold. This, taken together with the second premise (that P does not hold), is enough to guarantee that Q holds.

Example. The argument

> Either our measured data are wrong, or our analysis method is wrong. Our measured data are not wrong. Therefore, our analysis method is wrong.

takes the form of a disjunctive syllogism. It is valid.

Informal Fallacies

The fallacies presented above are examples of formal, deductive fallacies. Another part of logic, called *informal logic*, collects and classifies other types of fallacies that commonly occur in human discourse. People have committed these types of errors intentionally or unintentionally since the time of Aristotle (384 BC – 322 BC). Avoid them all.

Ad Hominem

We commit this fallacy when we argue against the person by attacking or discrediting him, or alluding to his possible motives.

Example. Here's an ad hominem argument from a student:

> Dr. Smith says that I have an error in my theory. But he gave me a bad grade in his class and has always had it in for me, so I think he is saying this just to hurt me. I don't think I can trust him, so I think he is wrong and I am right.

A professor could award a bad grade and still correctly identify an error in a theory. That's why this argument is fallacious.

Fallacy of Accident

We commit this fallacy when we try to apply a rule to a case it was not intended to cover.

Example.

> For safety, we store acids in glass containers. Hydrogen fluoride is an acid, so we should store it in a glass jar.

While it's true that acids are commonly stored in glass containers, hydrogen fluoride (or hydrofluoric acid) is used to etch glass. It obviously cannot be kept in a glass jar.

Straw Man Fallacy

We commit this fallacy when we distort someone else's position and then attack the distorted version.

Example.

> Ben, the postdoc in our research group, wants me to repeat the same measurement 20 times. Ben always invents busywork for us so he can impress Dr. Handley. I shouldn't have to repeat something 20 times just to make Ben look like he's doing his job. I won't do it, and I won't include it in the technical report.

In fact, Ben wants 20 repetitions as a good statistical sample. His intention is not to manufacture busywork for anyone.

Appeal to Ignorance

We commit this fallacy when we give up on further thinking and investigation. We might say, for instance, that event A must have caused event B because we cannot imagine any other reason for the occurrence of B.

Example.

> We were unable to show that the system is optimal, hence it is suboptimal.

The system could be optimal even though verification of this was seemingly out of reach.

Hasty Generalization

We commit this fallacy when we conclude something about all members of a group from the characteristics of an insufficient sample.

Example.

> The engineers with whom I interacted during my last job were all terrible writers. My new colleague John is an engineer. John must be a terrible writer.

John may turn out to be a great writer.

Post Hoc Ergo Propter Hoc

We commit this fallacy when we assert that event A must have caused event B because A preceded B in time.

Example.

> We lowered the temperature in the room in the morning, and our measurements were better in the afternoon. So measurements are better when the room is cooler.

The conclusion may be correct, but the argument form is still fallacious. Consider:

> I tied my shoes this morning and my measurements improved in the afternoon. Measurements are better when my shoes are tied!

Cum Hoc Ergo Propter Hoc

We commit this fallacy when we assert that event A must have caused event B because A and B occurred simultaneously.

Example.

> The street lamp went off right when I passed underneath. I must be controlling street lamps through some paranormal effect.

In fact, *street light interference* is a classic example of observer bias. Another example:

> The brakes in the car failed at the same time the alternator failed, so the alternator failure must have caused the brake failure.

In fact this could just be a coincidence, or both incidents could have the same cause.

Fallacy of Composition

We commit this fallacy when we erroneously attribute a trait possessed by all members of a class to the class itself.

Example.

> I checked the manual and found out that the quick-lock vise on the milling machine we want to purchase can only be set using metric units. I assume this must be a metric-only milling machine. Let's not get it.

Just because the attachment is metric doesn't mean the machine itself can't be set using English units.

Fallacy of Division

We commit this fallacy when we erroneously attribute the traits of a class of objects to each of the separate objects.

Example.

> American engineers produce many inventions each year. John is an American engineer. Therefore, John produces many inventions each year.

The statement refers to American engineers as a group. This group invents many things each year. From this we can draw no conclusion about John.

Begging the Question

We commit this fallacy when we use the conclusion we're trying to establish as one of our premises.

Example.

> The system is highly productive with minimal waste of energy because it is efficient.

The phrase "highly productive with minimal waste of energy" is a synonym for efficient. The argument being made is "The system is efficient because it is efficient." This is begging the question.

Weak Analogy

We commit this fallacy when we argue based on an alleged similarity between two situations that, in reality, are not that similar.

Example.

> Electric current is like water flowing in a pipe, and the battery is like a pump. When an old rusty pump gets clogged, it has trouble pumping water. Therefore, an old battery loses voltage because it gets clogged with electrons that it can no longer pump through the circuit.

In fact, the analogy between electric current driven through a circuit by a voltage source and water driven through a plumbing system by a pump is often used as a first explanation of electricity for children. It could be appropriate as a refresher for non-engineers as well. For the electrical engineer, however, it is certainly a weak analogy.

False Dichotomy

We commit this fallacy when we base an argument on the premise that either A or B must hold, when in reality a third possibility C could hold.

Example.

> The electric field must be either positive or negative, so it is definitely present and affecting our experiment.

In fact, the value of an electric field can be positive, or negative, *or zero.*

Fallacy of Suppressed Evidence

We commit this fallacy when we omit counterinstances while drawing an inductive conclusion.

Example.

> I couldn't adapt the old code for this new project because the vendor stopped supporting the language ten years ago.

OK, but you failed to mention that you're aware of several other versions of the language sold by competitors that should work perfectly well.

Fallacy of Equivocation

We commit this fallacy when we use a word in two different ways in the same argument.

Example.

> Since we built that 1:2 model of our prototype on such a large scale, we had better use the biggest scale we have to weigh it.

Fallacy of Amphiboly

We commit this fallacy when we argue based on a faulty interpretation of an ambiguous statement.

Example. Here's an example of amphiboly and equivocation together:

> I learned that the transistor dissipates 10 watts with the current experiment.

We don't know if it always dissipates 10 W, and you found out by running the experiment, or if it dissipates 10 W only during the experiment. That's amphiboly. We also don't know if you mean the *existing* experiment, or the experiment in which you measure electric current. That's equivocation. Remember, *current* has two meanings.

Appeal to the Crowd

We commit this fallacy when we argue that statement A must be true because most people believe it's true.

Example.

> Almost everybody uses Java to program these types of applets, so Java must be the best language for these applets.

Fallacy of Opposition

We commit this fallacy when we argue that statement A must be false because our opponent believes it's true.

Example.

> I've been working on this theory of friction for years. If you don't agree with it, you've obviously not considered it thoroughly.

Appeal to Authority

We commit this fallacy when we argue that statement A must be true because experts believe it's true.

Example.

> My advisor said that purple fribble has a small Young's modulus, so I could use it to build my device. Then I asked Dr. Smith, who said the Young's modulus isn't as small as my adviser claimed. Unlike my advisor, Dr. Smith is a full professor and department chair. He must be correct, so I'll use something else.

4.3 Additional Checks on Correctness

We have seen that an ability to recognize fallacious argument forms is essential to the engineer. In this section, we touch on other ways of catching errors in claims. We like to class these under the general heading of *physical reasoning*, although (1) many are quantitative or semi-quantitative in nature, and (2) we do not address the special reasoning modes employed by modern physicists. A fancier name is *heuristic reasoning*.

Intuitive Plausibility

Is the answer reasonable?

Example. Suppose we take an isolated particle and apply an external, unbalanced force directed to the right. If our calculation indicates that the particle responds by accelerating to the left, perhaps we should look for an error.

Dimensional Checks

Physical dimensions must appear consistently in a valid physical equation.

Example. Suppose we write

> The position along the x-axis of the particle at time t is given by
>
> $$x = x_0 + v_0 t + \tfrac{1}{2} a t^2 \qquad (1)$$
>
> where x_0 is the initial position, v_0 is the initial speed, and a is the acceleration (assumed constant).

The physical dimensions that appear in equation (1) are as follows:

$$[\text{length}] = [\text{length}] + \frac{[\text{length}]}{[\text{time}]} \cdot [\text{time}] + \frac{[\text{length}]}{[\text{time}]^2} \cdot [\text{time}]^2.$$

So all terms have the same dimensions (that of [length]), and this is *necessary* for the equation to be correct. Of course, it is not *sufficient*; it does not guarantee, for example, that (a) the numerical coefficient 1/2 is correct, or (b) there isn't a term missing from equation (1). Nonetheless, routine dimensional checks are a strongly recommended practice.

Example. If w, x, y, z all have units of length, then something is wrong with the equation

$$w = \frac{x^3 - y}{x^2 + z}\ .$$

Order-of-Magnitude Checks

Quantitative claims should be numerically reasonable.

Example. The electric currents that flow, under normal conditions, in a circuit operated by a small battery are probably in the mA (milliampere) range. They could be an order of magnitude larger or smaller than that, of course. Suppose Bill (an electrical engineering student) calculates a current in his hand-held circuit as follows:

$$I = V/R = 2.5/(10000) = 0.25 \times 10^3 = 250 \text{ A} .$$

Although Bill made a calculation error, he still has a chance to ask whether this answer is physically reasonable. Hint: The current in a cloud-to-ground lightning bolt might peak at several amperes.

Expected Variation with a Parameter of the Problem

Some engineering students associate the term *variable* with the term *letter*. But certain letters are conventionally used to represent true constants: examples are the Greek letter π and the base e of the natural logarithm. We would not call the corresponding quantities "variables" just because they are denoted by letters.

Other quantities in a problem may be denoted by letters but *temporarily held fixed during a calculation involving other variables.* We refer to these quantities as *parameters.*

Example. The equation $y = ax^2$ describes a *family* of parabolas: one for each value of a. To plot one curve from the family, we might set $a = 2$ and plot $y = 2x^2$. To plot another curve, we could set $a = 3$ and plot $y = 3x^2$. In plotting each curve of the family, we are holding a constant. On the other hand, a is not a "true" constant like e or π. It isn't appropriate to call a a variable or a constant: it is an example of a parameter.

Many problems of engineering interest involve parameters. By obtaining an answer in terms of parameters relevant to a problem, and by understanding how the answer to a problem *should* vary with each parameter, we gain an avenue for checking our final answer.

Example. Suppose we wish to find the volume V of a right circular cylinder having radius a and height h. In calculus we learn to set up the integral

$$V = \int_0^h \int_0^{2\pi} \int_0^a r \, dr \, d\theta \, dz$$

for this purpose. Although various letters appear on the right-hand side, they are not all "variables" at this stage of the game. The variables of integration are r, θ, and z; these are actually changing (over the ranges indicated by the integration limits) during the integration process. But h and a are fixed during the integration and are properly regarded as parameters. Completing the integration, we get an answer in terms of these parameters:

$$V = \pi a^2 h \ .$$

Now we can choose to mentally vary each parameter while holding the other one fixed. Holding a fixed and increasing h, we find that V increases according to this formula. This is, of course, as expected for a cylinder that is getting taller. Similarly, if we hold h fixed and decrease a, we find that V decreases as expected. Engineers should always be thinking in this way: we never tell our students they should reach an answer, box it in, and move on without mentally playing with each parameter in the answer. If they followed our advice, they would never be satisfied with answers such as

$$V = \pi a^2 / h$$

to the problem at hand.

The above example shows the value of solving problems using parameters. We could have treated a cylinder 1 m high and 10 cm in radius, thereby considering just one specific case. Instead, by using parameters, we obtained a formula giving the volume of any right circular cylinder.

Agreement with Known Special Cases

One advantage of working problems in terms of parameters is that a problem may have limiting cases whose answers are known.

Example. Suppose you must find the radial component of the electric field in the bisecting plane of a uniformly charged line segment of length $2L$. After a long calculation, you arrive at

$$E_\rho(\rho) = \frac{\lambda}{2\pi\epsilon_0\rho} \cdot \frac{\rho^2 + L}{(\rho^2 + L^2)^{1/2}}$$

where λ is the charge density, ρ is the perpendicular distance from the field point to the segment, and ϵ_0 is a constant called the free-space permittivity. Hoping for a quick quality check on this answer, you consider the trivial case in which $L = 0$; this will make the charged segment disappear and should yield a null result for the electric field. Unfortunately, you obtain

$$\lim_{L\to 0} E_\rho(\rho) = \frac{\lambda}{2\pi\epsilon_0\rho} \cdot \frac{\rho^2}{(\rho^2)^{1/2}} = \frac{\lambda}{2\pi\epsilon_0} \neq 0 \ .$$

There must be a calculation error. After finding and correcting the error, you arrive at

$$E_\rho(\rho) = \frac{\lambda}{2\pi\epsilon_0\rho} \cdot \frac{L}{(\rho^2 + L^2)^{1/2}} \ ,$$

which does behave correctly as $L \to 0$. Seeking a further check, however, you once again hold ρ fixed and let $L \to \infty$ to get

$$E_\rho(\rho) = \frac{\lambda}{2\pi\epsilon_0\rho} \ . \qquad (2)$$

Referring to an electromagnetics handbook, you find that this is indeed the field at distance ρ from a uniform line charge of infinite length. This is good news, but we still caution that it isn't a guarantee as many similar and not-so-similar expressions also reduce to (2) as $L \to \infty$. However, if your final answer *failed* to reduce to the known result (2), you'd know that a mistake was made somewhere (a mistake by you, by the person who derived (2), or both). Checking for agreement with known special cases is just one more tool you can use to hunt for errors in claims before you write those claims in your engineering document.

You can also run checks by approximating an answer: dropping small terms, ignoring slow time variations, etc. Such techniques often receive extensive coverage in engineering courses.

Other Mathematical Properties of the Answer

If an answer is time dependent, you might check its initial value, final value, or time-average value for correctness.

Example. Suppose your answer to a problem is a time function

$$y(t) = 4 + \cos 200\, t \ .$$

The average value of $y(t)$ is 4. If this seems wrong, you have reason to look for a calculation error.

Another good check is to look for inappropriate singularities.

Example. When solving the wave equation in cylindrical coordinates, it is often inappropriate to keep the Hankel function solution since it has a singularity on the z-axis. You may remember that this situation arises when finding the field inside a circular waveguide. If you cannot provide a physical reason why an electric field should be infinite, then your answer could be wrong.

Accord with Standard Physical Principles

Certain notions, such as causality and symmetry, are encountered routinely in physics. Why not use them to check your answers whenever possible?

Example. Suppose you must find the magnitude of the electric field at distance r from a point charge Q. After a page of calculations, you arrive at

$$E(r, \theta) = \frac{kQ}{r^2 + \theta^2}$$

where k is a constant and θ is the polar angle of spherical coordinates. Well, aside from the obvious problem with dimensions (you cannot add a distance squared to an angle squared), there is a problem with symmetry here. If we hold r fixed and vary θ, we are physically walking around the point charge while staying at constant distance from it. The symmetry of this extremely simple charge distribution implies a symmetry in the resulting electric field: it should *not* vary with θ. This gives you another reason to scrutinize your calculations.

Example. Suppose you seek the response of a physical system to a given input, and by a long calculation find that the response begins *before* the input is applied. This violates the accepted physical principle of *causality*: effects cannot precede their causes. Better look for a calculation error.

Another important principle is superposition, although one must remember that it applies only to linear systems.

Example. Often the whole cannot be greater than the sum of its parts. If you use 1000 tons of steel and 500 tons of concrete to construct a bridge, it is doubtful if the resulting bridge weighs 5000 tons (unless you have neglected to consider a component).

In contrast, the whole is often *smaller* than the sum of its parts because of cancellation. Two very large forces acting on a single bolt may produce little torque if the moment arms are the same and the forces are applied in opposite directions.

4.4 Other Ways to Be Careful

There are many ways to actively guard against the kind of sloppiness that leads one to make errant claims. Here are some suggestions.

1. Do not jump to conclusions. Stop and think. Review all available information. Seek expert help if necessary. Cover all bases before making a claim.

2. Maintain a critical attitude. Guard against distortions, whether honest or dishonest. Maintain reasonable skepticism even about the literature of your own field.

3. Respect the truth. You are not trying to find evidence to prove one of your preconceived notions. Rather, use an unbiased, calm mind to listen to what the evidence actually says.

4. Remember Ockham's razor. Prefer the simplest design or explanation.

5. Insist on reliable evidence from dependable sources. Your cubicle-mate's belief in something may not suffice for your purposes (that is, for your reader's purposes). He or she believes that electromagnetic waves travel faster than the speed of light? Perhaps this should be verified by an expert authority.

6. Double check everything! This takes additional time and effort, of course, but it may save the reader from having to evaluate false claims.

7. Always look for counterexamples to your claims. Look at each claim with a critical eye, trying to construct a counterexample. Any astute reader will be doing the same thing when reading your document.

Example. The *post hoc ergo propter hoc* and *cum hoc ergo proper hoc* fallacies should have you on alert about jumping to conclusions regarding cause-and-effect relations. Remember the old saying:

Correlation does not imply causation.

Sure, we may notice a strong positive correlation between two events X and Y. It *could* be that X causes Y. But it could also be the case that Y causes X, that both X and Y are among the effects of some cause Z, or that the observed correlation is just accidental. It often takes careful, planned experimentation to sort out cause-and-effect relations. An engineer's gut intuition cannot always be trusted in such matters.

4.5 Chapter Recap

1. Consideration of standard fallacies can teach us a lot about common thinking blunders.
2. Formal logical fallacies include denying the antecedent and affirming the consequent.
3. Informal fallacies include things like *ad hominem*, straw man, and appeal to ignorance. A quick summary of these fallacies appears on p. 155.
4. Many techniques are available for checking claims before the reader sees them.
5. The engineer should maintain a critical attitude and a respect for truth. One way to be critical of a claim is to seek counterexamples.
6. Don't jump to conclusions. In particular, correlation is not causation.
7. Ockham's razor (also spelled *Occam's razor*), a long-time favorite in scientific reasoning, is the principle that explanations should not be more complicated than necessary.
8. Spending the time to double check every claim is better than misleading the reader and becoming embarrassed in print.

4.6 Exercises

4.1. Identify the argument as valid or fallacious.

(a) All waveguides are inefficient. This resistor is inefficient. Therefore, this resistor is a waveguide.

(b) All ceramic capacitors are non-polarized. This capacitor is non-polarized. This capacitor must be a ceramic capacitor.

(c) All gold is diamagnetic. This metal is diamagnetic. It must be gold.

(d) All transistors are made of semiconductors. A diode is not a transistor. Therefore, a diode is not made of semiconductors.

(e) All rich people are happy. Some engineers are rich. Therefore, all engineers are happy.

(f) All Fourier transformable functions have a finite number of discontinuities in a given interval. The function $f(x) = x^2$ has a finite number of discontinuities in a given interval. Therefore, $f(x) = x^2$ is Fourier transformable.

(g) All passive two-port networks have $|S_{21}| \leq 1$. My network has $|S_{21}| \leq 1$. Therefore, my network is passive.

(h) All resistors are marked with color codes. This component has a color code. Therefore, this component is a resistor.

(i) All 3.5 mm connectors are precision connectors. Some RF connectors are 3.5 mm connectors. Therefore, all RF connectors are precision connectors.

(j) All K-connectors are precision connectors. All K-connectors are mechanically compatible with 3.5 mm connectors. Therefore, all connectors that are mechanically compatible with 3.5 mm connectors are precision connectors.

4.2. State whether the following argument forms are valid. Assume P, Q, R, S are statements.

(a) P or Q.
If P, then R.
If Q, then R.
Therefore, R.

(b) P or Q.
If P, then R.
If Q, then S.
Therefore, R or S.

(c) Not-R or not-S.
If P, then R.
If Q, then S
Therefore, not-P or not-Q.

4.3. Consider the list of *invalid* categorical syllogisms shown on p. 154. For each syllogism, find a real-world counterexample that shows the syllogism is invalid.

4.4. Look for fallacies.

(a) Smith's results are questionable because he has made significant errors in the past.

(b) Since it is impossible to conceive of anything but electromagnetic interference causing this problem, the problem must be due to electromagnetic interference.

(c) Having discovered failures in two of the modules tested at random, we concluded that all 10,000 modules likely failed.

(d) The system temperature increased after we heard the noise, hence the noise must have caused the temperature increase.

(e) Transistor leads are like tiny legs. Since people have two legs, transistors have two leads.

(f) Only two possibilities exist: either the temperature decreased or it increased. Since both of these represent changes, we do know that the temperature changed over time.

(g) This transistor is superior to the other alternatives because it is better.

(h) Resistors often have green stripes. Therefore, they seldom have blue stripes.

(i) All machines are somewhat inefficient. Sam is somewhat inefficient. Therefore, Sam is a machine.

(j) A resistor is an electrical device. A transistor is an electrical device. Therefore, a resistor is a transistor.

(k) There must be something wrong with subsystem A. Ever since it was redesigned, subsystem C has been unreliable.

(l) This new system is unreliable. Out of the 10000 units delivered to us, two random units were chosen for testing and both failed.

(m) We connected a 10 V capacitor and it exploded! We must have exceeded the voltage rating.

4.5. As humans, we have *cognitive biases* that lead us to distort our experiences and process information selectively. Do some background reading about cognitive biases. Could any of these patterns make it easier to commit fallacies?

4.6. Consult a logic textbook to learn the Venn diagram method for validating syllogisms. Use the method to validate the 19 syllogisms listed on p. 153.