

## THE MESSY WORLD WE INHABIT

ON AUGUST 1, 2007, the entire truss structure of the I-35W Bridge over the Mississippi River at Minneapolis, Minnesota, collapsed during the morning rush hour.<sup>1</sup> The horrifying catastrophe was over in just seconds. In the end, the disaster claimed the lives of thirteen motorists and injured 145 others. A series of lawsuits followed until finally, two years later, on August 23, 2010, the last lawsuit was settled, to the tune of \$52.4 million.

Subsequent to this spectacular engineering failure, no one was surprised that lawsuits were filed, and won or lost. Yet we wished it were not always so. Both engineering designs on the one hand, and their design contexts on the other hand, can be “bad” without there being a question of assigning blame. Granted, sometimes failure *can* be blamed on human error. And we readily admit that once the finger has been pointed and the offending culprit penalized, people tend to feel just a little bit better about the disaster, as though the weight has been lifted just a little. But can blame *always* be assigned? And if not, why do we assume that it can?

The habit of seeking someone to blame for engineering failures springs from a deep-seated temptation to view the world through an ideal lens. This temptation infects engineer and non-engineer alike. Yet for students of engineering, the temptation to think in an ideal mode can be made more acute by their exposure to certain aspects of the first- and second-year engineering curriculum. We will call these features, and the outlook produced, “ideal-world thinking.” Eventually, the very best engineering students unlearn ideal-world thinking, or at least learn to temper it with strong doses of skeptical realism. But in the meantime, ideal-world thinking hinders excellence in engineering and misleads ethical conversation. So, before we can get a handle on engineering ethics, we must begin

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by comparing the ideal world to the “messy world,” which is to say, the world in which we actually live.

### THE IDEAL WORLD

Take a good look at Figure 1.1. Gear A rotates at a speed of  $3.6\pi$  rad/sec. At time  $t_0$ , a point (P) is at the position as shown. Where will P be one minute later, at  $t_{60}$ ?

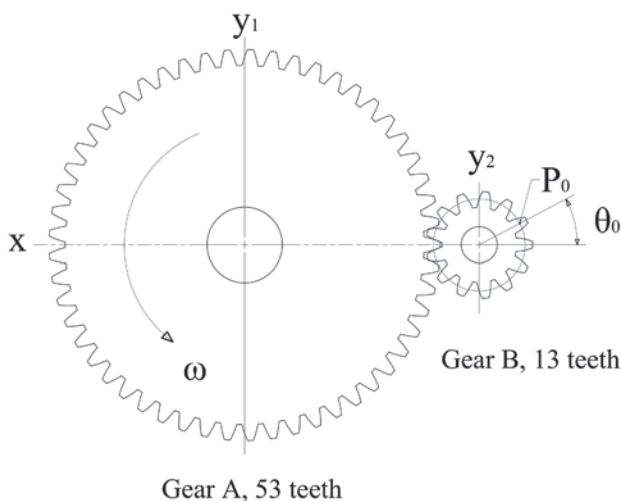


FIGURE 1.1 Calculating  $\theta$  for  $P_{60}$ <sup>2</sup>

For most readers, the calculation is very straightforward. The ratio between the gears is 53:13. Sixty revolutions of Gear A will correspond to  $(60 \times 53)/13$  revolutions of Gear B. Since whole revolutions can be discounted (all we're after is the position of P relative to the x-axis),  $^{3180}/_{13}$  will produce the same  $\theta$  value for  $P_{60}$  as  $^8/_{13}$  rotation. This rotation must be subtracted from  $\theta_0$ . We can tell from the diagram that  $P_0$  is  $^1/_{13}$  of a turn in the counterclockwise direction ( $2\pi/13$  rad or  $360/13^\circ$ ). So, if this were an exam, we could safely predict the final position of  $P_{60}$  to be  $(2\pi/13) - [8(2\pi)/13] = -7(2\pi)/13$  rad or  $6(2\pi)/13$  rad, if we measure  $\theta$  in the conventional counterclockwise direction (approx  $166^\circ$ ).

But hold on a minute. Haven't we shifted into calculation mode a bit too quickly? Where did this problem come from? Are we so familiar with textbooks that in rushing to find the answer, we may forget that an

engineering problem has a specific context in the real world where things can bind, bend, break off, melt, and so on?<sup>3</sup> The diagram *looks* official enough as the above magnification (Figure 1.1b) shows. In fact, it was generated by a program that takes almost no account of the physical limits of actual gear trains as well as the conventions of manufacturing. For example, it is standard to design gears with non-prime numbers of teeth. A gear train with prime numbered teeth can be built, but these are not stock and therefore would have to be special ordered. So why are the numbers of teeth in this particular diagram prime numbers (13, 53)? Is there a very peculiar and particular application behind this problem? (There is, actually. More on that later in the chapter.)

In addition to manufacturing conventions, a kinematician looking at this diagram spotted something else as well. The shape of the teeth is common enough—perhaps a  $20^\circ$  pressure angle. But there turn out to be *physical limits* to how few teeth can be meshed with 53 teeth without interference. For a  $20^\circ$  pressure angle, that number is 16. With 13 teeth as drawn, the interference will be such that the gears lock up.

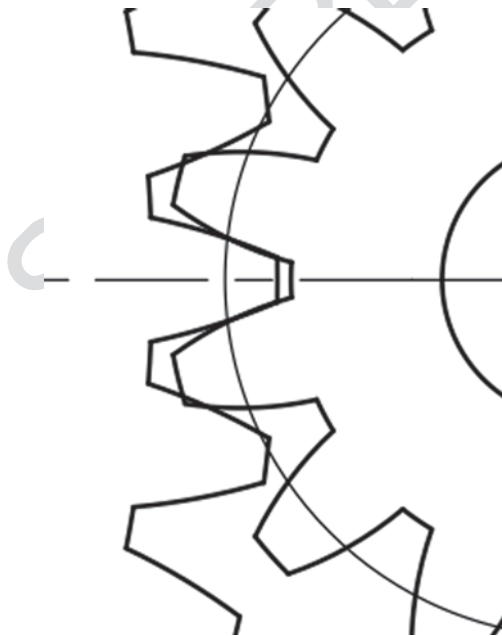


Figure 1.1b Detail of Custom Gear Train (53:13)

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To prevent interference, the teeth of the smaller gear must be “undercut”—indented a bit so as to allow the corners of the big gear teeth to rotate past as the gears turn. Undercutting gears may have an effect on load, since the smaller teeth are weakened. Real-world designers must ask, “What does the problem as posed presume about the load to be placed on this gear train?”

Okay, suppose we follow the *standard* methodology for gear train design and replace Figure 1.1 with the following stock gears.

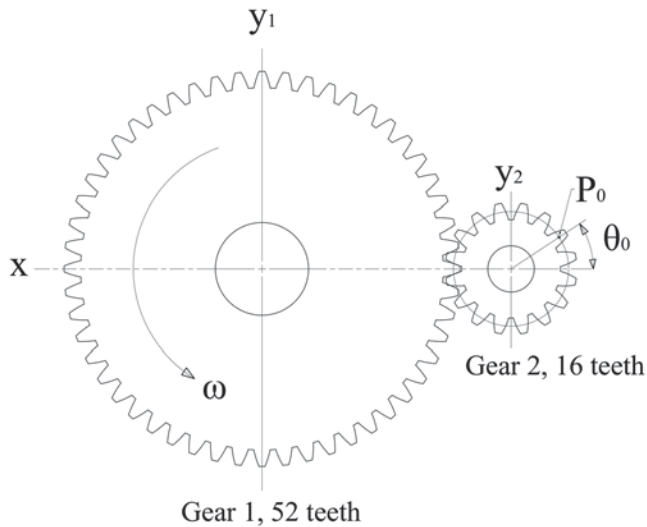


FIGURE 1.2 A “Stock” Gear Train (52:16)

Are we ready to solve? Maybe. Even the naked eye may be able to see that the “off the shelf” gears of Figure 1.2 appear to need undercutting. Moreover, we still don’t know what *kind* of problem we are facing. Is Figure 1.2 simply a thought experiment? Or is it a proposed design for some application in the real world where things bind, bend, break off, melt, and so on? If the application is real, we must ask: is the speed of Gear A at  $t_0$  real or merely assumed? Perhaps a client gave specs on the basis of assumptions rather than facts. This wouldn’t be the first client to have insisted on faulty specs! If we are intending to solve on the basis of the unverified assumptions of a client, then we are once again forgetting

to be engineers, because *engineers* must pose a *host* of clarifying questions to the client:

- Is the motor that drives Gear A running at  $t_0$  or is it at rest?
- How long does it take for Gear A to achieve 108 rpm (i.e.,  $3.6\pi$  rad/sec)? After how many revolutions can acceleration be ignored?
- How much “play” is in each bearing? If the bearings are liable to human adjustments, is there too much or too little play? Or is the play “just right”—as is the case with sealed bearings? Similarly, if the bearings are adjustable, then are the bearings adequately lubricated? (Or are we using sealed bearings?)
- How great a load is on the motor? After all, 108 rpm is quite slow as far as motors go. Is this a fast motor being made to work slowly by a large load? If so, bearing wear over time may be an important factor as  $t$  increases.
- Does the load vary?
- What is the temperature of the surrounding medium? What is the turbulence of the surrounding medium?
- Is the mechanism underwater? Underwater?! The diagram says nothing about the mechanism being underwater. But do clients always volunteer all the crucial details? Or do engineers need to *extract* pertinent information from sometimes unwitting clients?
- And so on . . .

These questions seem like trick questions, even traps. For asking questions like these, engineers are often branded as “glass-half-empty” pessimists. But in the real world, gear trains are not ideal. To think they are ideal would be to make a huge mistake. (“Real” is the actual, everyday world we live in where things bind, scorch, melt, break off, and generally fall apart. Mathematics may be used to *approximate* the real world—and not the other way around.)

For example, in 1986 General Electric switched from reciprocal compressors to rotary compressors in their refrigerators. They made the switch knowing that rotary compressors require more power and operate at higher speeds. But GE presumed that even at these higher speeds, rotary action was inherently closer to an “ideal” than reciprocal action and therefore inherently better. This sounds almost as if GE assumed rotary compressors behave *ideally*, as if they perfectly mimicked a technical

drawing of contextless gear trains comprised of frictionless revolute joints. Technicians reported no failures during the testing phase. But when the techs said that something about the new compressors “didn’t look right either,” GE decision-makers roundly ignored the lowly techs. Eventually these compressors *did* begin to fail. Twelve short months after one million refrigerators had been sold, the long-term effects of operating at higher speeds (and thus higher temperatures) became painfully visible: compressors bound, melted, broke, and burned out. It cost GE \$450,000,000 to replace the defective compressors.<sup>4</sup>

Back to our ideal gear train in Figure 1.1. When facing the problem of locating P at  $t_{60}$ , one student will answer “ $\theta = 6(2\pi)/13$  rad.” Another interrupts with a string of questions. *Which student gives the better response to the problem?* Well, doesn’t it depend on who is doing the asking and under what conditions? If we are in the classroom, we know that the ideal case *can* be diagrammed: point masses, frictionless bearings, instantaneous acceleration, infinitely solid grounding for revolute joints, etc. The ideal case has a single true answer, “For  $\omega = 3.6\pi$  rad/sec, P<sub>60</sub> is shown to be  $\theta = 6(2\pi)/13$  rad.” This answer can be delivered with *certitude*, because the ideal mechanism follows mathematically precise *rules*. These rules govern the ideal device with complete authority. In the ideal case, there is no wobble in the bearings because the bearings are completely snug yet frictionless. And yet . . .

### IDEAL-WORLD ETHICS?

Some people think, mistakenly in my book, that ethics is like the study of the rules governing the ideal mechanism. For these thinkers, a great deal of effort has gone into explicating the rules—even with mathematical precision, wherever possible. On this view, the job of the professional ethicist is to answer questions such as, “If human interaction is like an ideal mechanism, what *rules* govern person-to-person interactions?” Of course, human beings are not really mechanisms, and they concede that human interactions will sometimes deviate from the ideal, especially when they fail to follow the rules. But can ethics be modeled on the ideal? To find out, let’s take a closer look at one of these ideal-world models.

One proposed rule is this: human beings are obligated to behave in the manner that maximizes the likelihood of yielding the most quantifiable beneficial consequence for the greatest number of people. This rule, “maximize net quantifiable goodness,” is given by a series of calculations:

$$\text{Net } G_x = \sum_1^n (\text{likelihood})(\text{goodness})(\text{significance})$$

**EQUATION 1.1:** Calculating *Net Goodness* for course of action  $x$ , where  $n$  = the number of outcomes for course of action  $x$ , and  $l$  = likelihood,  $g$  = goodness, and  $s$  = significance of each given outcome  $n$

Suppose the boss has moved up a deadline that I was already struggling to meet. If I'm to stay on pace, I'll necessarily have to work longer hours than I'm already working—longer into the evenings (forget about my kids' soccer games) and big chunks of the weekend (forget about that anniversary getaway). On first thought four courses of action seem possible. I can (a) work the hours and take the lumps with my spouse and children; (b) appeal to workmates to help with my present task in exchange for the promise to help them out in the future; (c) say to the boss, "As you wish!" but in reality make no adjustments and simply fail to make deadline (perhaps I can apologize for this later); or (d) stridently refuse the boss's request, underlining my feelings by punching the boss in the nose. If these are my possible courses of action, then in the terms of the formula,  $x = 4$ .

Each course of action will have consequences of varying degrees of likelihood. For example, we can imagine that  $d$  (punch the boss in the nose) may result in one or more of the following: (1) I get fired; (2) I'm sued for bodily injury; (3) I break my hand; (4) I feel really good about myself; (5) I'm admired by my colleagues, who go on strike in solidarity with me until the boss is fired and I am promoted as the new boss. For this course of action (punching the boss), the possible number of outcomes listed is five ( $n = 5$ ).

For each of these three outcomes a *likelihood* ( $l$ ) is predicted and assigned a numerical value (such as "a 75 percent chance of occurrence.") The *goodness* ( $g$ ) of an outcome is a simple binary quantity: +1 if it is a good thing, -1 if it is a bad thing.<sup>5</sup> In the case of punching the boss, the first three outcomes listed are bad, or -1, but the last two are good, or +1.

Finally, the *significance* of the outcome is assigned a numerical ranking, say 1 for something trivial and 10 for something of grave importance. Getting fired is pretty serious—but not as bad as dying or being sued. So, perhaps we'll give it an 8. Being sued is worse than getting fired (since

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it goes on my permanent record), but not as bad as dying. So a 9 seems about right. Breaking one or more fingers is painful and inconvenient, but not as severe as losing the job. Let's give it a significance level of 5. Feeling good about myself is pleasant, but not more pleasant than a broken hand is painful; let's say a 3. Finally, my promotion into the place of my former boss is pretty sweet, maybe even a 9½ out of 10.

The *likelihood* of being fired is probably 90 percent or better; the chance of being sued depends on the boss's personality—let's say 75 percent. And the risk of breaking my hand stands at about 50–50. The chances of feeling temporarily very good are extremely high—the adrenalin rush virtually guarantees (100 percent) a brief elation. But the solidarity of my peers resulting in my promotion is extremely unlikely; let's say on the order of a 2 percent chance. Now we can do the math:

$$\text{Net G for Action}_4 = (-1)(8)(.90)+(-1)(9)(.75)+(-1)(5)(.50)+(1)(3)(1.0)+(1)(9.5)(.02) = -13.26$$

Of course we are only one-fourth the way done. If I can only think of four possible courses of action, then  $x = 4$  and I will generate four different calculations, four different Net G's. Thus the calculation must be repeated for the other three courses of action. Let's try one more calculation, say for Course of Action<sub>1</sub>, a.k.a. “do the work but take the lumps at home.” Four possible outcomes: keep my job (+8 at 100 percent); my wife takes the kids and leaves me (-9.9 at 10 percent); I am fined by the city for not mowing my lawn in a timely fashion (-2 at 15 percent); and having to cook for myself in my wife's absence, I lose 20 lbs. (+5 at 60 percent).

$$\text{Net G for Action}_1 = (+1)(8)(1.0)+(-1)(9.9)(.10)+(-1)(2)(.15)+(1)(5)(.6) = +0.8$$

After having carefully calculated the outcomes for these two courses of action, the obligatory thing to do according to this brand of consequentialism (called “utilitarianism”) is to give in to the boss and take my lumps on the home front. Why is this the “best” option? Because  $0.8 > -13.26$ .

One can see that if the scales are the same in each case (i.e.,  $l$  ranges from 0 to 100 percent,  $g = +1$  or  $-1$ , and  $s$  ranges from 1 to 10), then the goodness of an outcome can be *quantitatively* compared to other outcomes predicted for taking this course of action. The result of summing these values is the net G for *that* course of action. This string of calculations is repeated for each possible course of action; the course of action with the biggest total “wins,” which is to say—or so this theory *claims*—the one with the biggest total is revealed to be the *morally obligatory* course to take.



OBJECTIONS TO THE IDEAL-WORLD MODEL OF ETHICS

Of course, there are bound to be enormous problems with the quantification of moral value. After all, *likelihood* is terrifically difficult to predict in advance. Why? Because we do not live in an ideal world, but in a *complex and chaotic* one. “Complexity” and “chaos” are technical terms that mean no physical system, especially no living system, is entirely predictable.<sup>6</sup> This is not the same as saying nothing is predictable. (The flight of a baseball is pretty nearly a parabola.) The key term is *entirely*. Saying that no physical system is entirely predictable means that prognostication runs up against a limit.<sup>7</sup> But those who insist on thinking in ideal terms resist this conclusion and instead concoct ways for dismissing *all* the unknowns.

The most common strategy for dealing with unknowns in a decision-making scheme is to restrict the calculation to outcomes with a fixed likelihood, usually those conceded as certain ( $l = 100$  percent). This strategy means that the entire burden of comparative reasoning falls upon correctly ranking the relative significance (*s*) of each outcome. Of course, the idealists must be careful: assigning rankings can itself be a way to beat the odds. Since numerical rankings *mathematically guarantee* the conclusion, one might be tempted to play around with them until one gets what is wanted. In hopes of safeguarding against cheats, the idealists insist that the ranking be performed in the most publicly accessible denominator known to humankind: money.

Remember, the idealists want to perform a calculation of *Net Goodness*. If *goodness* is a simple +1 or -1, and *likelihood* is fixed at 100 percent, then the only remaining difficulty is in measuring *significance*. Unfortunately, in hedging the system against unpredictability and cheats, idealist decision-makers have inserted economics into the fray. The problem is this: Is market value a genuine measure of significance? Philosopher Caroline Whitbeck points out that we regularly do make various kinds of value judgments: “Van Gogh is a good painter,” “Gödel’s proof is a good one,” “Reading the Bible is good for you.” No doubt, each of these claims will have its objectors. Nevertheless, each claim is fully intelligible. We readily understand, and just as readily argue over, *aesthetic*, *logical*, and *religious* value claims. But as Whitbeck points out, *none* of these value claims translate into dollar signs. Van Gogh was a good painter *before* his paintings sold for millions.

Here’s the rub: Ascribing monetary “value” is really not an ascription of value. Monetary “value” does not reflect value; *it only reflects what the*

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*economic market can bear.* That being the case, the reliance on monetary value may lead one astray who attempts to perform a calculation for *Net Goodness* (as per Equation 1.1). Famously, in the late 1970s defense attorneys for Ford Motor Company argued that the corporation was blameless in the burn deaths resulting from exploding gasoline tanks in Pinto cars and light trucks.<sup>8</sup> They employed Equation 1 to make the case that Ford did exactly what the numbers obliged them to do: nothing.

The legal case boiled down to two courses of action: (1) recall and repair 11 million Pintos, and 1.5 million light trucks with the same design, by installing a bladder in the gas tank costing a measly \$11, or (2) do nothing and settle each lawsuit for wrongful death and property loss on a case-by-case basis. Let's do the numbers:

Outcomes (n = 3)	Likelihood	Goodness	Significance	Net G <sub>1</sub>
180 burn deaths	100 percent	-1	\$200,000	-\$36 M
180 serious burn injuries	100 percent	-1	\$67,000	-\$12 M
2,100 damaged vehicles	100 percent	-1	\$700	-\$1.5 M
Net G =				-\$49.5 M

FIGURE 1.3 Course of Action 1: Do Nothing

Outcomes (n = 2)	Likelihood	Goodness	Significance	Net G <sub>2</sub>
11 million cars	100 percent	-1	\$11	-\$122 M
1.5 million light trucks	100 percent	-1	\$11	-\$16.5 M
Net G =				-\$137.5 M

FIGURE 1.4 Course of Action 2: Recall and Repair with \$11 Tank Bladder

Astute readers often wonder whether the attorneys lowballed the numbers. And why were only *two* courses of action considered? Surely multiple courses of action were open to Ford once it learned of the design flaw. But for the moment, let's stay focused on whether "value" can be measured in dollars. In the Pinto case, the market supplied the data for both the value of a used Pinto (\$700) and human loss of life (\$200,000). When adjusted for inflation,<sup>9</sup> the approximate value of life in today's dollars would have been placed at \$635,000. This figure pales in comparison to the present market value of human life established by the EPA: \$9,100,000!<sup>10</sup>

Had Ford used the tenfold higher “value” in its calculations, it would have concluded that the morally obligatory course of action was to recall and repair all the tanks. (Just the 180 burn deaths at \$7.9 million produces a negative quantity of \$1.4 billion, which is almost ten times more than the cost of fixing the tanks!) As it was, Ford used the 1978 market value for life and concluded that, morally speaking, they were in the clear.

Such discrepancy doesn’t sit well with us. My older brother owned a Pinto back in the late seventies. Can I really believe that Ford would have been *blameless* had he died in 1978 but *guilty* if he had died in 2010 simply because the market value for his life had increased? Of course not. Our instinct is completely correct—loss of life is always an inestimably bad thing regardless of the market’s price tag. (Nevertheless, culture asks engineering firms to move forward with designs that are merely “safe enough.” A maximally safe airplane could never get off the ground.)

Equation 1.1 is called *consequentialist* because it is concerned with the outcomes or consequences of a given moral decision. When one uses it to help make a moral decision, one has to deal frankly with the inherent uncertainties of the equation. The form of the equation used by Ford’s attorneys is called cost-benefit analysis. As we have seen, it discounts uncertainty in the *likelihood* column by considering only those outcomes that can be conceded as given ( $l = 100$  percent). An alternative strategy for dealing with uncertainty in the equation is to fix the significance column ( $s$ ) instead of the likelihood. In other words, instead of conceding that certain outcomes are bound to happen and then assign a market value to each outcome, the alternative focuses on only one outcome—for example, loss of life—and then works to give precision to prediction of likelihood. Accuracy in prediction is attainable only when vast pools of data are available. For example, actuaries working for large insurance companies can show that the statistical chance of a red car crashing is slightly higher than the chance of a blue one crashing. No one knows for sure why. But given the millions of crashes by blue and red cars, the statistical difference in their rate of incidence is not negligible. This approach is called risk-benefit analysis. Risk-benefit analysis avoids the problem of “market value” because it is based on real-world data rather than the fluctuation of markets. Unfortunately, risk-benefit analysis cheats on the other end of the spectrum by severely restricting itself to immediate (or at least short-range) outcomes. But is this inherently more fair than the kind of confusion that “market value” injects?

Imagine a biologist considering taking a vacation cruise in the Indian Ocean. Socially minded fanatical friends urge the biologist not to go. Rather, they plead, the biologist ought to cash in her tickets and donate the money to relief efforts for the 1.5 million refugees still (in 2011) left homeless as a result of the 2009 Haitian earthquake. Ordinarily, we would say that the surrender of the price of one's vacation to charity is a noble deed. Such a gift might conceivably save many human lives. By lowering incidents of death, the risk-benefit form of the equation *decrees* that giving away the cruise money is even the *obligatory* thing to do.

But wait a minute. It is also conceivable, though in no way knowable, that a much-needed vacation might have a more beneficial *longer-range* result. Perhaps while the cruise ship is anchored in the bay, the biologist takes a day trip to the coast that brings her into contact with the farming practices of a local people, which in turn redirects her own research, resulting in the production of a pesticide that vastly increases grain harvests and feeds many more people than could have been fed by the surrender of the price of her ticket.<sup>11</sup> What I have done here is reminiscent of the work of ethicist Bernard Williams, who was fond of complicating apparently straightforward ethical calculations by the telling of simple, but realistic, stories about how we really live.<sup>12</sup> All such realistic tales remind us that the very best moral reasoning must consider the intangibles—those factors that we can neither predict in advance nor easily place a value upon, perhaps because they are longer-ranged than can be presently seen.

Williams's point about the importance of including such intangibles becomes persuasive when we consider the messy world that we live in with all its hurly-burly. But if we slip into thinking of the world in terms of ideal mechanisms, we may unwittingly overlook some of the very most important factors. Given the innumerable ways things can bind, melt, or break off, it seems unlikely that a good analogy for real-world ethics is that of an *ideal* mechanism. *Fortunately, there is another way.* As we shall see, this way is much closer to real-world engineering than to an ideal mechanism.

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Consider a second mechanical example, that of a Bianchi racing bicycle ridden by a fortysomething male competing in "Ride the Bear," a 105-mile road race over the highest paved road in Southern California. The problem of pressure angle disappears because the gear train has been replaced by chain and sprocket.

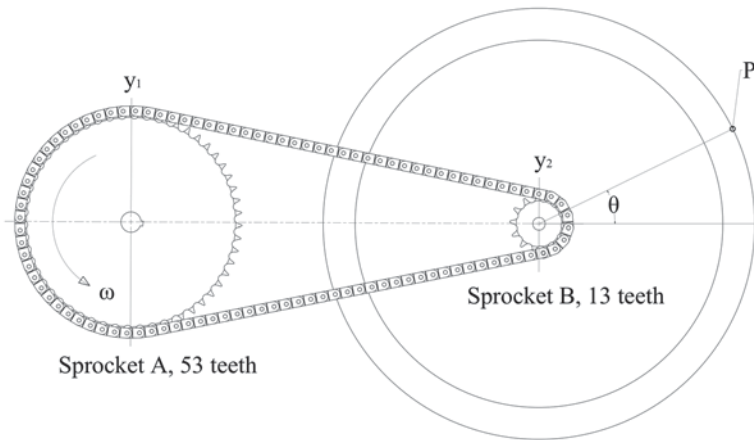


FIGURE 1.5 Bianchi Racing Bicycle with Rear Cassette Ratio 53:13

The ratio between the two sprockets is the same as in Figure 1.1, although in this case another member (the 700 mm wheel) has been added to the train. (In addition, the chain drive means that the rear cassette [sprocket] rotates counterclockwise, matching that of the chain ring.) The front chain ring has 53 teeth, which gives the racer a slight advantage on the flats over rivals who ride models that typically have 52-teeth chain rings. A smaller chain ring is available for climbing hills (it has 42 teeth; real bikers sneer at a 39-teeth chain ring—a.k.a. “Granny gear”—even for steep mountain climbs!).

Owners of racing bikes also have options for the sizes of their rear sprocket set (cassette). An easy set has sprockets with 25-23-21-19-17-15 teeth. The largest sprocket (25) makes for easier uphill climbing. Similarly, a set with much smaller ratios (e.g., 21-19-17-15-13-11-9 teeth) will give the rider more downhill velocity but will be more difficult to pedal. The 23-21-19-17-15-13 set on this particular Bianchi was a good compromise for me. As the owner of this seafoam-green Bianchi, I had the entire middle range of ratios covered and had no problem climbing aggressively (forty-five miles of “The Bear” was uphill). But my top speed was capped at 52 mph. Unless I was in free fall, I could only go as fast as I could spin; and it was physically impossible for my then fortysomething body to exceed a short-burst cadence of 145 rpms (which for 700 mm tires and a maximum gear ratio of 53:13 produced  $P_{ave} = 52$  mph).

Seen from the view of a cyclist, *none* of the interrupting questions raised about the ideal gear train in Figure 1.1 are insignificant. The “load” on the “motor” is constantly varying as terrain shifts. So, “instant acceleration” was impossible, as was steady cadence ( $\omega_{\text{ave}}$  only approximates  $220\pi$  rad/min.). Friction is *constantly* the enemy. Having one’s bottom bracket properly adjusted for optimum range of play was *crucially* important. (Had my Bianchi not been a classic, I’d have opted in a heartbeat for the modern sealed-bearing bottom bracket.) Bearings are *always* in danger of binding and overheating and scoring their races. The ticking noise that developed in my bottom bracket was not only the symptom of its eventual demise; it also reminded me that this was *not* a frictionless system I was pedaling. Air temperature—which in Southern Cal could easily top 100°F—was important data to consider when strategizing how to keep the human “motor” from overheating. (Overheating from lack of water was obviously of greater concern than “bonking,” or “hitting the wall,” which results from lack of food. When both aerobic and anaerobic fuel have been digested, the body begins to digest itself.) Ironically, when we reached Lake Arrowhead, almost a vertical mile higher than the start, the temperature was in the low 40s). Nor were air speeds negligible. Obviously, if ambient air is still, racers create their own headwind. But with the added bluster of the seasonal Santa Anas, the gusts of which top 50 mph, keeping one’s balance was almost as challenging as making headway. (When the Santa Anas swept down Devil’s Canyon during an earlier training ride, I had to *stand up in first gear on the flats*.) And stability of the “motor mounts” are of no small consequence: when my head tube tore in half (apparently a failure long in the making) on a particularly steep training ride, my “motor” lost perhaps one-third of its climbing power, since I could no longer pull on my handle bars nor safely throw the frame from side to side.

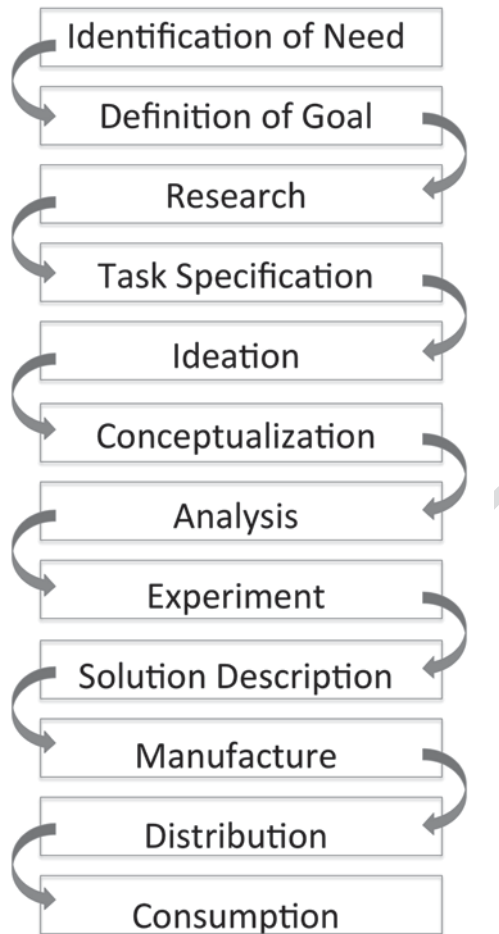
All questions about context, which rudely interrupt so-called ideal design, are parameters that cannot be ignored if one wants to be a happy biker. “Happy” or “successful” or “good” cycling has only minimally to do with “rules” (obey traffic laws; be courteous to fellow riders by pointing out road debris when they are drafting, etc.). Moreover, happy cycling also has relatively little to do with the principles that have been extrapolated for the ideal mechanism.<sup>13</sup> But it has *everything* to do with real-world messiness: incompletely described scenarios littered with imperfect data and ever-changing conditions. This messiness is the terrain that all human beings share. Mechanical engineering prof Billy V. Koen says that coping with the messiness of the real world makes us all “engineers” of a

sort. Human reasoning is none other than the engineering method. Thus Koen describes the engineering method as “a strategy for causing the best change in a poorly understood situation within the available resources.”<sup>14</sup>

In this book we are going to scrap the idea of ethics as the ideal case and look at ethics as something messier. Ethics is more like the real-world activity of designing and racing bicycles than it is calculating  $\theta$  for  $P_{60}$  on a technical drawing. But we must be careful! At every step along the way, we will be sorely tempted by the sheer attractive simplicity of the “ideal” case. One way to counter this temptation is to constantly force ourselves to “look and see.” We must always ask ourselves, “What is *really* going on here?”

For example, think of how engineering students are initially taught design. At least on the first pass, design is typically taught as a straight-line process. From the textbook diagrams it is easy to imagine that one turns the crank at one end and out pops the innovation at the other end. Consider Figure 1.6 on the following page, depicting the “science” of design from a standard text.

SAMPLE



**FIGURE 1.6** A Typical Diagram Depicting the “Science” of Design<sup>15</sup>

Now, to be fair to the professors, it is common practice to initiate students into new material with ideal types and later ramp up the complexity of description as students get a more realistic grip on things. (Hopefully, you have already met some of these correctives in your more advanced coursework.) Notice in this diagram that the design process is laid out like a production sequence on an assembly line. Because we are already prone to interpret technical drawings as ideal machines, to use such a diagram of the design process misleads some into thinking that design is analogous to an ideal mechanism (predictable, clear boundaries, etc.).



As they learn, students hopefully graduate to better diagrams, ones that depict the interaction between “stages” as bidirectional, with double arrows indicating feedback loops from subsequent stages.<sup>16</sup> At one point in his publishing, Stuart Pugh used something like the following diagram to convey the design process.

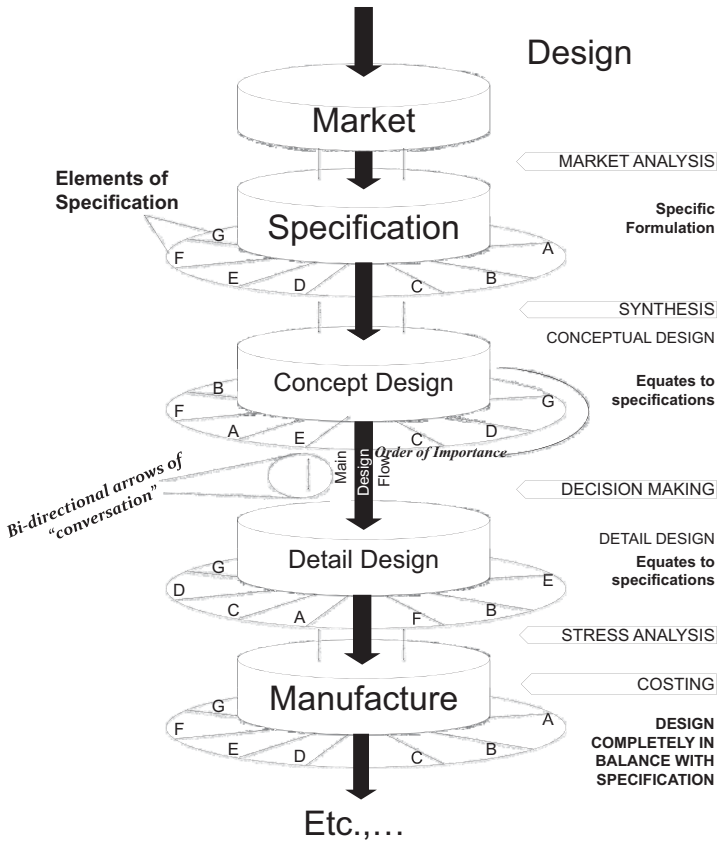


FIGURE 1.7 Design Core<sup>17</sup>

You'll notice two things. First, there are bidirectional arrows, which indicate conversation between subsequent stages. Of course, the small size of these arrows relative to the whole seems to suggest that cross-level conversations are at best concessions and at worst interruptions to the overall march toward production, shown by the thick, black downward arrows. Second, the parameters—what Pugh will later call “design boundaries”—are not only rankable, they have been given clear ranking (A through G, “in order of importance”). But of course, in the real world things are *much* messier than this. All “stages” have feedback into all other stages. And rankings of design boundaries can only be definitively completed retrospectively. That means it is artificial to say when one stage ends and another begins. Of course, without identifiable stages, the diagram falls apart and ceases to teach anything at all. So the diagram may hint at design as a regular process, but design doesn't really happen this way.

Oddly enough, designers seem to get along just fine despite inhabiting an undiagrammable situation. Real-world design is not straight-line, or even bidirectional; it is “loopy.” There are iterations of conversations between various stages. However, these iterations are not inherently convergent, like iterations of the algorithm for calculating the square root of 2. Successive iterations of the square root algorithm give an increasingly precise answer. But in the design process, sometimes further iterations of conversations between stages corrupt, even ruin, a good design. Consequently, teams need to figure out when to *stop* iterating. But the “time to stop” is itself a metric whose optimum cannot be spelled out in advance. Messy, yes?

In addition to the linearity implied about design, there is a second danger lurking in the oversimple diagram. Such diagrams make it look as though the terms in which the project is negotiated are *clear to everyone at each step along the way*. Obviously, there will be disagreements to be sorted out. But the diagram makes it appear that the terms of negotiation are understood by each player: “What problem are we solving? What are we making? How will it function? What metrics ought to be optimized? What issues are open for negotiation? Who has what stake in the outcome?” And so on. But answers to these questions are all achieved—sometimes very slowly and painfully—over time.

So, what is design *really* like? Perhaps design is a bit like a medieval quest, like the search for the Holy Grail. With only the vaguest of ideas about what is sought (What's a “grail?”), a team of relative strangers, whose powers—both singly and together—are untested or uncertain, launch off

in some direction. Along the way tests will be faced that will prove mettle, hone skills, clarify what they seek, and reveal how best to keep seeking. A map (or “diagram”) could only be constructed retrospectively, *after* the deed is done. In other words, even if a map had been available at the outset of the quest, the nature of a quest is such that, on the front end of the journey, the questers would have been as mystified by the map as they were by the journey itself. (If a group knows where they are going, how to get there, and what they are after, we say they are taking a “trip” rather than going on a quest.) And perhaps engineers often enough require “trips” rather than quests. But we must stay open to the possibility that engineering design often has a quest-like character in order to learn what this is.

The real world is messy. As wonderful and powerful as mathematics and the hard sciences are, they do not perfectly describe the actual world we live in. We live in the messy one. And engineers make the amazing progress they do by remembering that it isn't the real world that approximates math and science. Rather, *math and science are the approximations*. Don't misunderstand: math and science are the very best approximations we can possibly have. In fact, we ought to work hard to mathematically model not only, say, general principles of kinematics, but also all the imperfections involved, such as acceleration ( $dv/dt$ ) and friction ( $\mu$ ) and so on. And of course, advanced models *do* begin to account for these deviations.<sup>18</sup> But the important difference between scientists and engineers is that whereas science aspires to express an ideal world, engineers *use* both math and science *as tools* for approximating *the real world we actually live in*. That is why the final bar for the engineer is never a theory or a mathematical model, but “look and see”: Does it work? Does it work well *enough*? This is not to say that idealized models ought to be completely ignored. Most often, an ideal picture clears the workspace for design; proposals that *defy* the ideal picture do not even make it onto the table. Most often—but not always. For there are cases in which engineering *precedes* science. James Watt had a functioning steam engine long before the first thermodynamics text was written. And centuries before Bernoulli, Eilmer of Malmesbury glided six hundred feet wearing homemade bird's wings!<sup>19</sup> (He was quite possibly the only one ever to succeed. Sadly, he broke both legs in landing and remained crippled the rest of his life.) An infamous episode in the history of civil engineering illustrates the bewitching mystique of the ideal picture.

Early in the twentieth century, road building, like many other fields in engineering, depended on a “look-and-see” approach. That is, the

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skilled eye and trained hand of the experienced practitioner constituted an “empirically derived understanding of nature.”<sup>20</sup> In other words, what counted as expertise *inside* civil engineering resided in the know-how of the expert practitioner. Unfortunately, what outsiders wanted was numerical proof.<sup>21</sup> Without “proof” people mistook engineering for a “low-tech” enterprise, forever destined to be less respectable than the more quantitative and “scientific” fields such as electricity (for which the mathematical ideal governs more closely). Some civil engineers felt the urge to “keep up with the Joneses” and tried to justify the expertise they already possessed in their fingertips by collecting numerical data to prove to outsiders what they themselves already knew. This turned out to be a wild goose chase. So, for a time, the federal Bureau of Public Roads (BPR) scrapped the field-testing of new road materials and designs. Rather, they moved the data gathering into a controlled lab environment in the search for repeatable numerical results. For example, the BPR devised a complex machine for simulating the way a truck pounds pavement. The device numerically measured the impact made by a heavy weight falling two inches (the sort of blow a truck delivers when it drives off a two-inch plank). The device was then complexified to simulate any size truck. Yet in order to keep the experiment properly “scientific,” only one variable (weight of vehicle, height of drop, thickness of pavement, the type of underlying soil, etc.) could be altered per trial. After months, even years, of testing, the BPR had collected exhaustive data—but only for *a single* kind of subsoil! Drainage of the soil was not even on the radar. Nor was the effect of the recoil action of truck springs initially considered. Still, federal road builders doggedly followed the BPR data and began constructing roadways that were thick at the center—where the wheels touched most often—and thin at the edges.

Fortunately, a number of states, perhaps too poor to afford the equipment and too much in a hurry to wait for yet more federal experiments, simply laid down sixty-eight sections of road, each about fifty yards long, with various designs, thicknesses, materials, soils, and drainage patterns, and then assigned a fleet of trucks (from 2,500–13,500 lbs.) to drive on it nonstop. Eventually, fifty of the sections were pounded into failure. The surviving eighteen sections were deemed superior designs. Some of the results were intuitive (e.g., concrete outperformed brick). But one result was startling: the best road design was one that was thick at the edges and thin in the middle, the very *opposite* of the conclusion demanded by BPR’s theoretical ideal.

The lesson to be learned? Don't succumb to the bewitchment of thinking you have the ideal answer. In an ideal picture, or an idealized model, there is always the implication that if we look hard enough, we'll find the single correct solution. But in the messy world, things are different. This is not to say that anything goes. In the absence of a single correct solution, we are not thereby free to do whatever pleases or amuses us. No! Some proposals are clearly wrong. (For example, those that simply do not work or cannot be built.) However, *there may be more than one right solution*. In all fields of engineering the activity taken in response to the messiness of the actual world, when no answer is to be found in the back of the book, is the real field of *engineering design*.

## CONVERSATION IS CRUCIAL TO DESIGN

In this book we shall discover that *engineering ethics is analogous to real-world engineering design*. There is no substitute for actually doing design work en route to learning what design is. But short of field experience, we shall have to rely on the observations of those who have taken the trouble to "look and see." Louis Bucciarelli, professor at MIT, has done just that. After shadowing three different teams doing three unique projects for three separate firms, Bucciarelli was able to spell out why design was neither straight-line nor ideal. His short answer is that *design is a social enterprise that at its core is a conversation spoken in a language of its own invention*. How thoroughly does conversation impinge on good design? On Bucciarelli's view, to the extent that designers talk unwillingly or incompletely, design will inevitably succumb to entropy, or "design degradation." We know that degradation certainly enters through *manufacturing* stages of engineering.<sup>22</sup> But Bucciarelli observed that degradation can result not only from short cuts in manufacturing, but also at the design table. This is plausible if we remember that designers are neither omniscient nor morally perfect. Perhaps one designer unwittingly competes with others.<sup>23</sup> Or perhaps another's emphasis on cost reduction conflicts with someone else's goal of going green. Only in the classroom does the assigning of weights for evaluation happen *a priori* (which is to say, prior to looking and seeing). In the real world these metrics must be *negotiated*.<sup>24</sup> Sometimes these negotiations are both risky and painful.<sup>25</sup>

Depending upon student maturity, design may be introduced to the students by any number of helpful first-order approximations: there are straight-line models, ones that describe overlapping phases, ones governed

by computational algorithms, and so on. Whatever pedagogical model is employed, novice students first encounter “design” in the abstract, cut off from actual persons who do actual design work. But real-world engineering design doesn’t happen in the abstract any more than it happens by itself. So, engineering students must graduate to the realization that design is something that *people* do. It doesn’t make sense to talk about “design” without at the same time talking about people. Each person at the table brings his or her unique blend of skills to the task. But people also complicate things.

Bucciarelli observed that at the outset, each designer, whatever the team, conceives the to-be-completed “object” in ways that differ from her compatriots. In Bucciarelli’s words, each team member inhabits her own “object world.” The activity of design means bringing our object worlds together by talking long enough until the worlds begin to blend. But at the outset, team members are almost consigned to speak foreign languages with each other.<sup>26</sup>

Perhaps Plato can help us understand Bucciarelli’s point. Plato once told a parable about blind persons each describing one part of an elephant by touch and then drawing conclusions about the whole elephant! Feeling a stout leg: “This beast is like a tree!” Feeling the long nose: “This beast is like a snake!” The same sort of thing might happen if each participant spoke a different language in addition to being blind. It would take a very long time to come to terms if everyone were describing the elephant’s parts spoke a different language. But Bucciarelli is not talking about French or English. He isn’t even thinking about different dialects. He is referring to *sublanguages within* English. Since none of us know the half-million or so words in the English language, it seems likely that entire conversations go on without us being able to understand a single sentence. So, there may be many, many more sublanguages that might be in play than we might first imagine. Still, it’s hard to believe Bucciarelli when he says that even within a design firm, like IDEO or OXO, each designer speaks a language unique to her. But perhaps the best policy for our investigation is to “look and see.”

For example, in the now famous five-day redesign of a shopping cart, the design firm IDEO utilized a team in which engineers were outnumbered by non-engineers (such as linguists, biologists, marketers, psychologists, etc.). Some will say that IDEO takes this mixed sublanguage approach to the extreme. But Bucciarelli observes that the multiple-languages problem plays out even in ordinary engineering firms in which every designer is

an engineer by training.<sup>27</sup> While both electrical engineers and mechanical engineers have taken calculus, electrical engineers inhabit a quite different object world than do mechanical engineers. Here is a simple example: “resistance” means one thing when talking about a gear train and another when talking about an electronic circuit.

The challenge of a team’s eventually achieving fully functional communication about design—whether the intended artifact is a shopping cart or a large-scale real-time X-ray inspection machine—is not easy. Getting everyone on the same page is not a simple compromise over vocabulary. Nor did Bucciarelli observe designers using a fat dictionary to *translate* from X’s world to Y’s and from Y’s to Z’s. Rather, in the world of design, *a team evolves its own unique sublanguage*. Bucciarelli reports that this often is “a matter of convention and custom,” involving “curious practices and forms of expression as well as tokens and grammar, jargon and idiom,” not to mention sketches, analogies, metaphors, models, and prototypes.<sup>28</sup> In short, the design team evolves its own mother tongue.<sup>29</sup> And the only way to learn it is by immersion. One has to participate in design in order to become fluent. This may take time, but achieving fluency is worth it. Granted, designers probably won’t describe their gains in terms of “fluency.” But they will notice that their work with each other has begun to “click.”

Here are some of Bucciarelli’s observations on the way design work “clicks,” which is to say, the way designers evolve their own design language.<sup>30</sup>

1. The language spoken by the team becomes somewhat “self-contained.” Outsiders to the team do not have an automatic ability to understand what the team is talking about without direct participation in the group. In fact, early on designers quickly discover that direct translation from each proper object language to another (say from electrical engineering to marketing) is simply not possible. Consequently, in order for one designer to communicate to her peers, she must resort to vernacular rather than her own technical object-world language.<sup>31</sup>
2. Outsiders find that the best way to learn the team’s evolving language is to approach it like a foreign language and learn fluency by immersion. Granted, some of the language is codified in handbooks, standards, and textbooks that are widely accessible to outsiders. (Thus, for example, as a bicycle racer I shared a small overlapping understanding with mechanical engineers who designed the bike and technicians

who kept it running.) But these “canons” are not exhaustive. (Even if they were exhaustive, a book couldn’t tell one which vernacular use of a term [e.g., “resistance”] is in play. You may have already met this phenomenon while reading the history of science. Compare early modern conceptions of “ether” with  $\text{CH}_3\text{OCH}_3$ , or late nineteenth-century definitions of “force” with  $F = ma$ .) Some of what makes for “good” design in the task at hand cannot be understood except as the language is learned on location by means of the hands-on *activity* of designing.

3. As might be expected, mathematics shows up a lot in technical object worlds. However, Bucciarelli observed that the mathematics of one designer’s “world” only *resembles* the math of another world, since the *particulars* to which math is applied may comprise distinct sub-languages. Bluntly put, mathematics is *not* the universal language; it is more like the *precondition* for learning to speak.
4. A design team’s language is fluid. On the one hand, it is settled enough to give direction to the flow of the conversation. But like a riverbed that is ever shifting, so too the boundaries of a given design language may drift over time.<sup>32</sup> For example, a feature that yesterday exemplified “good” design may today be discarded by the design team for other meanings of “good.”
5. No one person is a privileged elite with a god’s-eye view or superior fluency that encompasses all the sublanguages spoken. “Fluency” in the object language of this design team is something achieved by everybody on the team, albeit haltingly. The team as a whole achieves fluency in their locally evolving sublanguage as each member struggles to make her unique ideas intelligible by means of conversations, shouting matches, e-mails, diagrams, sketches on napkins, etc.
6. Words—both ordinary and specialized vocabulary—are obviously crucial for mastering an evolving design language. But equally important are sketches, prototypes, heuristics, metaphors, hands-on experience, and tacit know-how. Surprisingly, mathematical models are often idealized and thus leave off the very particulars that are needed for gaining tacit know-how of the object world. As a result, mathematical equations and technical drawings can supplement but never *displace* the need for rough-and-ready, garden-variety *words*.

So we see that design involves both the ideal and the rough. In the main, design is something like learning to communicate with foreigners



without help of a dictionary. Design is decidedly *not* the straightforward application of an ideal picture.

## CONCLUSION

If design were governed by an ideal, it is conceivable that every design team that responded to a RFP (request for proposal) would generate identical solutions. The likelihood that each of us has met insufferable know-it-alls who treat *their own* design proposal as the *only* one logically possible does not change the reality that design is as unpredictable as it is messy. The outcome of design activity is not like cranking the gear train in Figure 1.1 and asking for the location of  $P_{60}$ . Another turn of the crank results in a fully predictable result. Rather, design work undertaken in response to a new problem turns out to be messy business. And as Bucciarelli has shown, design is as messy a business as learning to cross the communication gaps created by the existence of as many object worlds as there are team members!

From Bucciarelli's record of his work shadowing the three design teams actually practicing design, one lesson that emerges is the need for a certain kind of personal character. In particular, there is the need for a basic level of trust among designers on a team.<sup>33</sup> It is only on the basis of a very primitive trust that children are able to learn language from their parents. So, too, designers must trust in each other. In addition, they must trust in the common nature of the way the world works even when that cannot be exhaustively spelled out. Because, after all, design is this team's way of dealing with their world just as engineering as a whole is the human means for dealing with the messy world. In short, *design is a social process for coping with the messy world.*<sup>34</sup>

## DISCUSSION QUESTIONS

1. Does mathematics approximate the world or does the world approximate mathematics? Why?
2. What are the two most common forms that consequentialism takes?
3. Under what conditions is the consequentialist formula most useful for decision-making in ethics? What are the limits of this formula?

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4. What does Bucciarelli mean by the term “object worlds”? What do you gather Bucciarelli means by saying each design team evolves its own language?
5. Why do you think one has to *participate* in design in order best to learn it?

## NOTES

1. Live footage of the incident can be viewed on YouTube.com, e.g., <http://www.youtube.com/watch?v=osocGiofdvc>.
2. The diagrams of gear trains and sprocket arrangements was done with the help of Bingjue Li on a CAD program called “Inventor.”
3. My guide in these matters is frequently the engineer-turned-philosopher Ludwig Wittgenstein. He was very concerned with a certain blindness we develop when we look at the world around us. “The machine (its structure) as symbolizing its action: the action of a machine—I might say at first—seems to be there in it from the start. What does that mean?—  
“If we know the machine, everything else, that is its movement, seems to be already completely determined.  
“We talk as if these parts could only move in this way, as if they could not do anything else. How is this—do we forget the possibility of their bending, breaking off, melting, and so on? Yes; in many cases we don’t think of that at all.” Wittgenstein, *Philosophical Investigations*, §193.
4. This spectacular debacle is recounted in Ferguson, “How Engineers Lose Touch,” 16–24.
5. This may seem overly simplified. But notice that if the goodness of an outcome is mixed, both good and bad, the outcome must be broken down into component parts that are each either entirely good or entirely bad.
6. In this book I’ll use the terms “chaos” and “complexity” to refer to the irreducible and systematic unpredictability that underlies all the apparent mathematical regularities of the physical world we live in. The fact that we cannot exhaustively predict future events except statistically (*pace* the popular television series *Numbers*) means that humans live in a *contingent* world. For further reading see Russell, Murphy,

and Peacocke, *Chaos and Complexity*. See also Juarerro, *Dynamics in Action*; Mitchell, *Unsimple Truths*.

7. The French mathematician Henri Poincaré showed that even in simple linear systems like billiard balls colliding, an error in the  $n$ th decimal place leads to total uncertainty after  $n$  collisions. “Linear” does not mean “traveling in straight lines,” although billiard balls tend to do this. “Linear” here means solvable with simple algebra. Conservation of momentum, equations using  $mv$ , does not require differential equations to solve. See Polkinghorne, *Science and Providence*, 28–29.

Systems of physical measurement inevitably run up against Heisenberg’s uncertainty principle. Given Planck’s constant, Poincaré’s work leads to the conclusion that linear systems—those solvable by simple algebra rather than differential equations—become entirely unpredictable after something on the order of 30–40 or so collisions. How then do Rube Goldberg devices work? (For example, see Honda’s “The Cog”: [http://www.youtube.com/watch?v=\\_ve4M4UsJQo](http://www.youtube.com/watch?v=_ve4M4UsJQo).) I suspect that such devices have moments of “re-start”; rather than being actual pre-predicted chains of 50+ collisions, they are groups of shorter chains, each ending with a binary event rather than a continuation of the series. For example, a good pool player may be able to regularly pocket a ball after three collisions. The pocketing completes the chain. The act of falling into the pocket is not unpredictable as if instead of falling into the pocket, a fourth precise collision needs to happen.

8. The details of this case are easy to find. See, for example, Hoffman, “Ford Pinto.”
9. The conversion factor for 1978 dollars is 0.314. Inflation adjustment data from the Web site maintained by Oregon State University: <http://oregonstate.edu/cla/polisci/individual-year-conversion-factor-tables>.
10. The numbers vary: the federal Transportation Department uses a figure close to \$6 million, whereas the FDA has declared a life was worth \$7.9 million. Appelbaum, “As U.S. Agencies Put More Value on a Life, Businesses Fret.” See also Fahrenthold, “Cosmic Markdown.”
11. This story has precedent. The Neem tree has been used for centuries by continental Indians as a pesticide. In 1992 W. R. Grace tried to establish a patent on the active ingredient derived from Neem, *azadirachtin*. See Severance, Spiro, and Werhane, “W. R. Grace & Co. and the Neemix Patent (a),” 399–409.

12. Perhaps the most famous of these involves a botanist named Jim who stumbles upon a village in the Amazon basin while looking for flowers. “Jim finds himself in the central square of a small South American town. Tied up against the wall are a row of twenty Indians, most terrified, a few defiant, in front of them several armed men in uniform. A heavy man in a sweat-stained khaki shirt turns out to be the captain in charge and, after a good deal of questioning of Jim which establishes that he got there by accident while on a botanical expedition, explains that the Indians are a random group of inhabitants who, after recent acts of protest against the government, are just about to be killed to remind other possible protestors of the advantage of not protesting. However, since Jim is an honored visitor from another land, the captain is happy to offer him a guest’s privilege of killing one of the Indians himself. If Jim accepts, then as a special mark of the occasion, the other Indians will be let off. Of course, if Jim refuses, then there is no special occasion, and Pedro here will do what he was about to do when Jim arrived, and kill them all. Jim, with some desperate recollection of schoolboy fiction, wonders whether if he got hold of a gun, he could hold the captain, Pedro, and the rest of the soldiers to threat, but it is quite clear from the setup that nothing of that kind is going to work: any attempt at that sort of thing will mean that all the Indians will be killed, and himself. The men against the wall, and the other villagers understand the situation, and are obviously begging him to accept. What should he do?” Yikes! Cited in Pojman, *Ethical Theory*, 191–92. See also Mulhall, “Mortality of the Soul,” 355–79.
13. Remember that mathematical “laws” are unattainable asymptotes for real machines. As such, *math approximates reality* and not the other way around. Math is at best a “rule of thumb” for real-world problems. More on this in chapter 3.
14. We will later consider his more complete definition: “the engineering method is the use of heuristics to cause the best change in a poorly understood situation within the available resources.” Koen, *Discussion of the Method*, 9, 28.
15. Adapted from the diagram by Hill, *Science of Engineering Design*, 49. Notice that the book’s title pairs engineering with “science” rather than the older understanding of engineering as an art form. *Ars mechanicus* will be explored in chapter 10.

16. Despite drawing the specious analogy between design and the scientific method, Hill does note that, perhaps unlike science, design requires the iteration of some steps along the way. See *ibid.*, 36–38. Similarly, Stuart Pugh acknowledges bidirectional feedback between stages of design. However, Pugh downplays this give and take on grounds that feedback diminishes as design progresses. See Pugh, *Creating Innovative Products Using Total Design*, 267–68.
17. Compiled from various diagrams used by Pugh over the course of his lifetime. See Pugh.
18. However, even here we must be careful. Modelers cannot account for all the imperfections. Every computer model divvies up reality into chunks in order to make the calculations manageable. It is precisely here that engineers are in danger, when they forget to consider the modeler’s assumptions. See Ferguson, “How Engineers Lose Touch.”
19. White, “Eilmer of Malmesbury.”
20. Seely, “Scientific Mystique,” 675–702.
21. For an account of math used rhetorically, see Seife, *Proofiness*.
22. For example, the Boston Tunnel was originally designed to be tiled with metal-plated porcelain. Unfortunately, this expensive tile was substituted with cheaper, but much heavier, concrete ones. Famously, five three-ton ceiling sections failed and crushed a car, killing a woman on her way to the airport. Wald, “Late Design Change.”
23. Amélie Rorty has written a clever satire showing how blindness sets in among team members. See her “How to Harden Your Heart.”
24. Bucciarelli, *Engineering Philosophy*, 20.
25. *Ibid.*, 14. For a much more technical account of design discourse, see Bucciarelli, “Between Thought and Object,” 219–31.
26. “. . . different forms of expressions go hand in hand with different ways of thinking about the world, about the existence of conceptual entities—their ontological status—and about the meaning and scope of the principles and requirements of the different paradigmatic sciences that frame thought and practice within object worlds. My framing of design as a social process in which different participants work within different object worlds which, in some restricted sense are incommensurable worlds, leads me to claim they *speak different languages*.” Bucciarelli, *Engineering Philosophy*, 15. Whew! That’s a mouthful. By

the way, why do professors write in such a complicated fashion? Might it be that sometimes profound or complex ideas can only be expressed in profound or complex ways? Could you explain differential equations to a ten-year-old?

27. Bucciarelli writes about three firms he shadows and their three respective design problems: a photovoltaic array for lighting highways in Saudi Arabia, a problem of dropout in quality for images of a high quantity photo-printer, and an X-ray machine for inspecting large cargo crates. Bucciarelli, *Designing Engineers*.
28. Bucciarelli, *Engineering Philosophy*, 15.
29. “. . . object world language is a *proper* language.” Ibid., 16.
30. Ibid., 16–21.
31. In Bucciarelli’s terms, “object worlds are incommensurable.” Ibid., 20.
32. Wittgenstein, *On Certainty*, §§99, 97, 256.
33. This kind of trust toward others is one example of what Danish ethicist Knud Løgstrup called “the sovereign expressions of life.” Or what John Howard Yoder called working “with the grain of the universe.” Hauerwas, *With the Grain of the Universe*; Løgstrup, *Ethical Demand*.
34. “Different participants with different responsibilities, competencies and interests, speak different languages when working, for the most part alone, in their respective domains (electrical circuits, kinematics, linguistics, psychology, and so on). For this to ring true, we ought to construe language in the broadest terms—to include the sketch, the prototype, the charts, even a computer algorithm as elements employed in the productive exchange among participants. But individual effort within some disciplinary matrix does not suffice: *Designing is a social process; it requires exchange and negotiation as well as intense work within object worlds.*” Bucciarelli, *Engineering Philosophy*, 21. Emphasis added.