

Chapter 2

Decisions and Mistakes

2.1 Section 16. Human Foibles

To understand human decision-making, it is necessary to distinguish between how people make decisions when they behave rationally and when they don't [1]. A rational decision requires a goal, perfect information, and an optimal course of action that maximizes the expected value of the decision. This is the *prescriptive* model of decision-making [2]. This is how people *should* make decisions in an ideal world. In such a utopia, there is a shared single goal, decision makers (DM) have access to all requisite information and they possess the cognitive capacity to use that information efficiently. Furthermore, they know all options that are available to them and the consequences of each option. They must also have the time and resources to make the requisite computations. If these conditions are satisfied, then the optimal course of action can be described as the one that, in the long run, is more valuable (or profitable) than any other course of action [3].

As an illustration of rational decision-making, consider a coin-flipping contest with the following rules. If you call heads and the coin comes up heads, then you win \$10. If you call tails and the coin comes up tails, you win \$1. Otherwise, you get nothing. Would you call heads or tails? Rational individuals would choose heads, because that would maximize the amount of money that they expect to get. The expected value of choosing heads is 0.5 (the probability of a heads) times \$10 (the value of the bet) equaling \$5. Whereas, the expected value of calling tails is 50¢.

In contrast, a *descriptive* model describes how people actually do make decisions. This model is discussed in the following pages. Typically when making decisions there is always some uncertainty and insufficient time and resources to fully explore the problem space. Therefore, people are unable to make rational decisions [2]. To explain what people actually do in this situation, Herb Simon [4], the renowned Noble Laureate, coined the term *satisficing*. Simon postulated that people do not even attempt to find an optimal solution. Rather, they search for *good enough* alternatives, that is, alternatives that *satisfice*. Similarly, engineers seek

satisficing designs. Unlike philosophers, engineers tend to be pragmatic. While philosophers might spend endless hours trying to phrase a proposition so that it can have only one interpretation, engineers strive to be unambiguous to the extent feasible, given time and cost constraints.

Humans are not rational. Mark Twain's refrain, "It ain't what you don't know that gets you into trouble. It's what you know for sure that just ain't so," makes this point nicely. Humans can often be very certain of knowledge that is simply false. Let us see how. Consider the following questions. What major American city is directly north of Santiago Chile? If you travel from San Diego, California to Reno, Nevada, in what direction would you travel? Do you think that there are more words that start with the letter r, than there are with r as the third letter. Answers to these questions are likely to provide instances of erroneous information that we carry in our heads. Consider the first question. What American city is directly north of Santiago, Chile? Most Americans would say that either New Orleans or Detroit is north of Santiago, instead of Boston, as shown in Fig 2.1. Now consider the second question. If you were traveling from San Diego to Reno, in what direction would you be going? Most Americans would suggest that Reno is northeast of San Diego, instead of northwest. Furthering this thought train, which end of the Panama Canal is farther west, the Atlantic side or the Pacific side? Most people would say the Pacific. Now the third question. Because it is easier to visualize an r at the beginning of a word, most people think that there are more words that begin with r, than have r as the third letter.

Here is another example of the brain reaching a conclusion that contradicts the facts. Identify an imaginative person, preferably one that knows you. Family and friends work best for this. Ask if he or she wants to participate in an interesting demonstration. Get him to extend his arms in front of him, straight and relaxed (the way one expects a zombie would). Tell him to close his eyes and imagine that he is holding a bucket in his left hand. Not only is the bucket heavy, but it is getting heavier because he is holding it under a tap with running water. Tell him that the bucket is filling up with water and getting *heavier and heavier*. Emphasize the word "*heavier*." Now, tell him to imagine a string tied around his right wrist. The string is attached to a blue helium-filled balloon. The balloon is trying to rise, pulling his hand up in the process. Tell him that as the bucket gets heavier with the inflow of water, the balloon tugs more on his wrist pulling his arm up.

Now, watch his left arm. If the subject has a vivid imagination, and you have performed the "experiment" correctly, you should see his left arm drop from the weight of the water bucket while his right arm gradually rises from the upward pull of the balloon. Now, with his eyes still closed, ask him to tell you where his arms are. If he has not already noticed the effect (most people become aware of the effect while their eyes are still closed), tell him to open his eyes and look at his arms. Surprise!

It is entirely possible that this experiment may not work for you, because it does not work for everyone. It works by the power of suggestion, and works best on people with good imaginations and after you have practiced it many times on your friends. If it does not work for you early on, practice may change that. You can draw

encouragement from Dave Baldwin [5], a major league pitcher with a career 3.25 ERA, who famously wrote that if you lose a game, don't blame the umpire or your teammates; just go home and practice harder.

Here are a few more questions that people tend to get wrong.

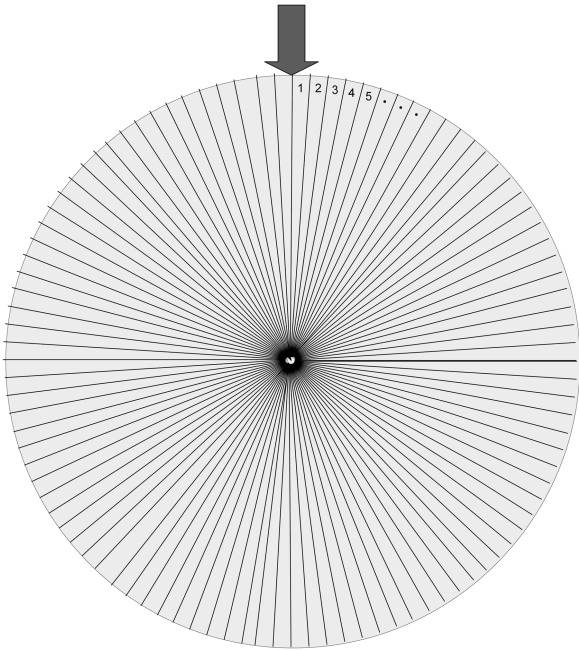
- A blind beggar had a brother who died. But the dead man's brother is not the blind beggar. What relation was the blind beggar to the brother who died? Think about this for a bit, to make sure you get it right. Brother is not the answer: the answer is his sister. Most people make an erroneous implicit assumption about gender, in this case, that the blind beggar is a man. Making unwarranted assumptions is all too common in engineering design and decision-making in a variety of contexts.
- Here is another interesting question that people are likely to get wrong. How much dirt is there in a hole that measures 2 ft by 3 ft by 4 ft? Take a moment to calculate this number. That's not it! Remember, a hole does not have dirt in it!
- Homicide, diabetes, and suicide are three common causes of death in the United States. List them in order of frequency of occurrence from the most to the least. Jot down your answer on a piece of paper, right now. In actuality, there are more suicides than homicides, but since they do not draw media attention, they do not rank high in your head. The correct order is diabetes, suicides, and then homicides. The point of these examples is that humans carry erroneous information in their minds.

Cognitive illusions can also impair decision-making. We call them illusions because people tend to believe them with as much certitude as they do optical illusions. The following example of a cognitive illusion is from Piattelli-Palmarini [6]. In this study, people were shown a wheel of fortune with numbers from one to hundred (Fig. 2.2). Then the wheel was spun. Sometimes the wheel pointed to a low number such as one, two, three, four, five, or six, and the subjects were then asked a seemingly off the wall question like, "How many African nations are in the United Nations?" They responded and their answers were recorded. How about you? How many African nations do *you* think are in the United Nations? Please write that number on a piece of paper. The cognitive illusion of this example is called anchoring. When estimating numerical values, a person's first impression dominates all further thought. Continuing this example, sometimes the wheel pointed to a high number like 95, 96, 97, 98, 99, or 100. The subjects were then asked, "How many African nations are in the United Nations?" They responded and their answers were recorded. How about you? How many African nations do *you* think are in the United Nations? Please write that number on a piece of paper. Here is what happens. If the wheel showed a small number such as five, then the subjects inevitably underestimated the correct number. On the other hand, if the wheel showed a large number, such as 97, then their subjects inevitably overestimated the correct number. Did you? This shows that a random unrelated event, like spinning a wheel, can predispose answers to questions. The point here is that humans are not always reliable decision makers, because they often carry erroneous information in their heads without actually knowing it [7].

Fig. 2.1 Map showing that Boston is directly north of Santiago Chile



Fig. 2.2 A wheel of fortune with numbers from 1 to 100



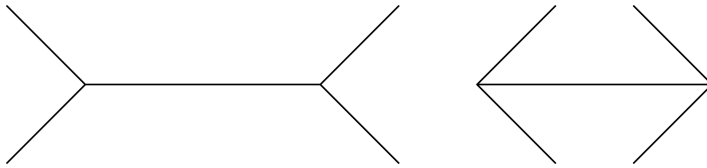


Fig. 2.3 The Müller-Lyer illusion

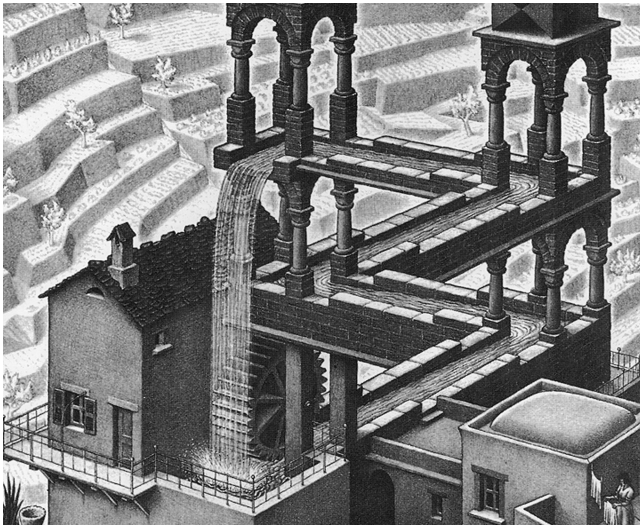


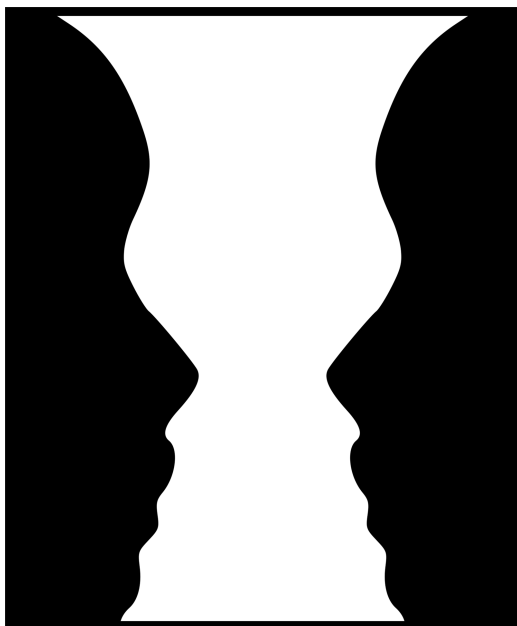
Fig. 2.4 M. C. Escher's waterfall

To make matters even worse, the information humans gather with their senses is often wrong. In 1641 Descartes [8] wrote that our senses “sometimes misled us; and it is the part of prudence not to place absolute confidence in that by which we have even once been deceived ([8], *Meditations I*, paragraph 3).” Probably the most famous example of our visual sense misleading us was created by Franz Müller-Lyer in 1889. In Fig. 2.3, which of the two horizontal line segments do you think is longer? Although your visual sensory system tells you that the one on the left is longer, a ruler will confirm that they are of equal length.

Some other examples of our visual sense deceiving us are Escher's waterfall (1961) and Rubin's vase (1915). In Escher's waterfall of Fig. 2.4, let your eyes follow the flow of water. Then explain this apparent perpetual-motion machine. In Rubin's sketch, do you see one white vase in the middle or two black human profiles on the sides? You can see the vase or the profiles, but not both at the same time (Fig. 2.5).

The tactile system sensory system can also deceive us. Imagine this experiment. Put your left hand in a big bowl of cold water and put your right hand in a big bowl of hot water, for around a minute. Then put both of your hands in a big bowl of

Fig. 2.5 Edgar
Rubin's vase



lukewarm water. The lukewarm water will simultaneously feel warm to the left hand and cold to the right hand. In 1690, John Locke [9] referred to such an experiment explaining “how water felt as cold by one hand may be warm to the other.”

When two sensory systems contradict each other, there will be problems. For example, if a man were below deck on a ship in a troublesome sea, his vestibular system would tell him that he was moving violently, but because his head would be moving with his visual frame of reference, his visual system would tell him that he was stationary. This conflict between sensory systems would cause seasickness. Going above deck, where he could see the horizon, might relieve it.

Two sensory systems can combine to confuse us. In the taste–temperature illusion, putting an ice cube (which has no taste) on the side of the tongue will give rise to a clearly perceptible salty taste sensation. In this case, delivering a sensation via one sensory modality (temperature) gives rise to a sensation in a different sensory modality (taste). Another example of two sensory systems combining to confuse us is when we think a dummy is speaking the words of a ventriloquist. Magicians are also adept at exploiting such foibles of our sensory systems.

In summary, our senses mislead us. This puts false information in our minds. Our minds further muddle this information and then we make decisions based on this knowledge. Good luck!

2.1.1 Homework

2.1.1.1 Ethics 1

One of issues that comes up in the business world is the practice of giving and accepting gratuities. When do you accept them and when do you reject them? In some cases, it is a fine line—is it a gift without any thought of receiving anything in return or is it a gift with the idea of “courting” a favor? The following is a typical case.

Scott Bennett is the engineer assigned to deal with vendors who supply needed parts to the Upscale Company. Larry Newman, sales representative from one of Upscale’s regular vendors, plays at the same golf club as Scott. Larry and Scott are old friends from grade school.

One morning they go off in the same foursome. Sometime during the round, Scott mentions that he is really looking forward to vacationing in Florida next month. Larry says his uncle owns a three-bedroom condominium, on the water, in Florida that he rents out during the months he and his family are up north. Larry offers to see if the condominium is available next month—assuring Scott that the rental cost would be quite moderate.

The next day Larry calls Scott and tells him that he can rent his uncle’s condominium for \$200 a week. “My uncle,” Larry says, “gets nervous when he rents to total strangers. He likes to have reliable people stay in his condo; the condo is paid for, and my uncle isn’t interested in making money on it—he just wants a little help meeting basic operating expenses and the taxes.” Scott accepts the offer and begins making plans for his vacation.

1. Would you consider this a gratuity?
2. Would you accept Larry’s offer?
3. Would this sway your judgment if, at some point in the future, you were analyzing products offered by Larry’s company?

2.1.1.2 Ethics 2

Jack and Jill had a baby while they were Assistant Professors at a university. The department head and the faculty were very supportive, gave them special assignments, and reduced their teaching loads so that they could care for their child. Then, Jill had an affair with Sam, another faculty member, and divorced Jack. At one time Jack and Jill were both assigned to the department committee evaluating the annual faculty reports. Most people expected them to recuse themselves, when it came to evaluating Jack, Jill, and Sam. But surprisingly, Jack said, “We are divorced, but we are on good terms. I will not nix her. I can fairly evaluate her.” Jack had a reputation for being honest. So no one objected. Subsequently, Jack evaluated Jill much higher than his average for the other faculty members and higher than the rest of the

committee did. Similarly, Jill evaluated Jack much higher than her average for the other faculty members and higher than the rest of the committee did. What ethical problem existed here?

2.1.1.3 Ethics 3

In the future, when you are an expert in some domain, you may become a consultant, either as a member of a consulting company or on your own. Assume that you have had a relationship with a particular company for a long time. It is a good contract; it pays well and is solid income. It comes time for a review with the president of that company. You have been studying their system/process for weeks and you discover that it is seriously flawed. You have written a report that details the mistakes and offers ways to fix most of them. What should you put in your presentation? If you write a hard, accurate presentation, it will embarrass the people who did the original work. The boss will be forced to fire either you or them. In almost all cases, it will be easier to fire you. You could use euphemisms to point out the mistakes without stating how serious they were. But here your suggestions would also have to be weak. You could present your suggestions for improvement, without saying that their system had mistakes in it. You could praise the company and say that they have a very good product, with just a few things that might be improved. Finally, you could say that their product is good and you would keep your consulting job for another year. What would you do?

2.1.1.4 Erroneous Knowledge

Dale Carnegie's book *How to Win Friends and Influence People* stated that humans only use 10 % of their brains. It suggested that reading the book could help people to use more of their brains. Do you think this is true?

Could our brains contain as much as three million miles of neural connections?

Are some people left-brained and others right-brained?

Can subliminal messages influence people to buy products?

Is it reasonable to think that playing Mozart's music to infants or college students will increase their reasoning abilities?

Is adolescences an inevitable time of psychological turmoil?

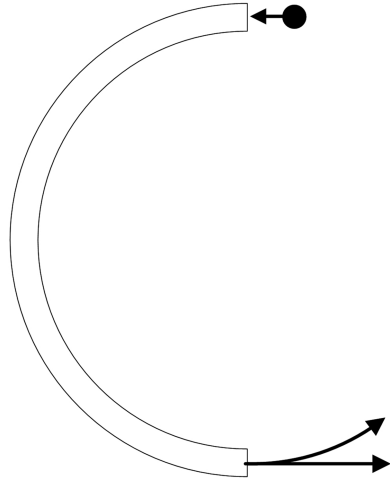
Is hypnosis useful for retrieving memories of forgotten events.

Do you think that IQ tests are biased against certain groups of people? (Fig. 2.6)

These questions and our answers are from

<http://emilkirkegaard.dk/en/wp-content/uploads/50-Great-Myths-of-Popular-Psychology.pdf>.

Fig. 2.6 Which path will the ball follow after it leaves the tube?



2.1.1.5 What Color Is the Bear?

A hunter in his camp saw a bear one mile directly south. He stealthily crept to that location. But by the time he got there, the bear had traveled one mile directly east. He shot the bear and walked directly to the dead bear. Then he dragged the bear one mile directly north, back to his camp. What color was the bear?

2.2 Section 17. Prospect Theory

Prospect theory is a widely accepted theory of how humans make decisions . It was developed by the psychologists Tversky and Kahneman¹ [11]. This theory explains the subjective nature of the human decision-making process in terms of heuristics and biases that are present in the assessment of information, and the commonly observed deviations from rational decision-making that result.

At this point, we need to define a few terms. *Value* reflects the *objective* worth of an item. For example, the present market value of an ounce of silver is about \$17. *Utility* is a *subjective* measure of the happiness, satisfaction, or reward a person gains (or loses) from receiving a good or service. *Objective probability* means a number derived from observations of and/or experiments on real-world events. *Subjective probability* means a number in your brain that reflects your knowledge

¹Kahneman won the Nobel Prize in Economics in 2002 “for having integrated insights from psychological research into economic science, especially concerning human judgment and decision-making under uncertainty” [10]. Tversky did not share this prize because Nobel prizes are not awarded posthumously.

Fig. 2.7 Four variations of the expected value model

	Objective Probability	Subjective Probability
Objective Value	EV Expected Value	SEV Subjective Expected Value
Subjective Utility	EU Expected Utility	SEU Subjective Expected Utility

of the frequency of an event. *Expected value* is, roughly speaking, the mean or average value of a function. Now we wish to examine combinations of value, utility, objective, and subjective probability.

There are two types of probability: objective and subjective. Objective probability is usually based on experiments and measurements. It was invented by Pascal [12]. Subjective probability is used to describe a person’s mental model of the likelihood of a thing being true. It was invented by Locke [13].

Human decision-making is based on probability, value, and utility, Smith [14]. Figure 2.7, based on Edwards [15], differentiates four variations of the expected value model. The upper-left quadrant represents the rational, normative, or prescriptive mathematical theory of expected value (EV) , where objective probabilities and values are considered. This is a rational model, it is independent of the opinion of any individual. The upper-left quadrant is free of heuristics and biases. It is the economist’s model for human decision-making, maximizing expected value. The lower-right quadrant of Fig. 2.7 represents the subjective, behavioral, biological, descriptive theory of Subjective Expected Utility (SEU) , where subjective probabilities and subjective utilities are used. The two bottom quadrants involve subjective utility, while the two right quadrants involve subjective probabilities.

Thus, there are two models (or views or theories) of human decision-making: the prescriptive and the descriptive. The *prescriptive* model in the upper-left quadrant prescribes how economists say that humans *should* make decisions in accord with a rational calculus when the objective probabilities are multiplied by corresponding objective values to give the overall expected value. The *descriptive* model in the lower-right quadrant describes what humans actually do.

For 40 years (from around 1950 to around 1990) economic theories used a *prescriptive* model to describe how humans made decisions. The fundamental assumption of their model was that humans are rational. In contrast, the most accepted *descriptive* model of human decision-making is prospect theory, developed by Kahneman and Tversky, [16], which explains the nature of the subjective human decision-making process in terms of the heuristics and biases present in the

assessment of information, and the common deviations from rational decision-making that result.

The Subjective Expected Utility model and prospect theory differentiate between actual probability and subjective probability. What they called subjective probability is what John Locke called probability. Locke stated that probability is the degree to which a person believes something to be true. “Probability is likeliness to be true. . .” Locke [13].

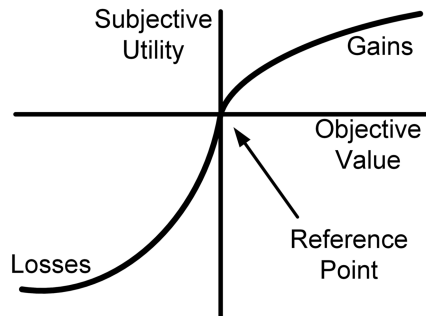
Our knowledge, as has been shown, being very narrow, and we not happy enough to find certain truth in everything which we have occasion to consider; most of the propositions, we think, reason, discourse—nay, act upon, are such that we cannot have undoubted knowledge of their truth: yet some of them border so near upon certainty, that we make no doubt at all about them; but assent to them as firmly, and act, according to that assent, as resolutely as if they were infallibly demonstrated, and that our knowledge of them were perfect and certain. But there being degrees herein, from the very neighborhood of certainty and demonstration, quite down to improbability and unlikeness, even to the confines of impossibility; and also degrees of assent from full assurance and confidence, quite down to conjecture, doubt, and distrust: I shall come now, (having, as I think, found out the bounds of human knowledge and certainty) in the next place, to consider the several degrees and grounds of probability, and assent or faith. Locke [13].

Thus, Locke thought that humans have a mental model for what Stephen Courbet called *truthiness* [17] of each proposition. This value would run, say, from 0 to 1, representing, respectively, belief that the proposition is completely false and belief that the proposition is completely true. This is subjective probability.

2.2.1 Subjective Utility

Prospect theory divides subjective decision-making into a preliminary screening stage and a secondary evaluation stage. The effect of these two stages is that values are considered not in an absolute sense (from zero), but subjectively from a reference point established by the subject’s perspective and wealth before the decision. This psychological process is a part of framing. Figure 2.8 shows how objective values translate into subjective utilities [16].

Fig. 2.8 The change in human subjective utility versus numerical value according to prospect theory, Kahneman and Tversky [16]



The three important points shown in Fig. 2.8 are that (1) gains are valued about half as much as losses (the slopes near the reference point are in a 1-to-2 ratio), (2) gains and losses are relative to a reference point, \$10 means a lot more to a poor man than to a rich man, and (3) both gains and losses show saturation (slowly approaching upper and lower limits). This graph will go in the lower-left corner of Fig. 2.7.

There are dopamine cells in the ventral tegmental area (VTA) of the human brain that respond like this. Their firing increases if the reward exceeds the reference expectation and decreases if the reward is less than expected.

Even with the requisite knowledge and resources, people tend to not make rational decisions, because they do not evaluate utility rationally. Most people would be more concerned with a large potential loss than with a large potential gain. Losses are felt more strongly than comparable gain, as is shown in Fig. 2.8. Which of the following wagers would you prefer to take?

- A \$2 bet: you win \$2 with probability of 0.5, or \$0 with probability 0.5. For example, we put down a two-dollar bill and flip a coin to see if you get it or not.
- A \$1 bet: you win \$1 with probability of 0.99 or \$1,000,000 with probability 0.00000001. For example, we put down a one-dollar bill and a state-lottery ticket. If the lottery ticket is a winner, you keep the \$1 million, else you keep the dollar bill.
- A \$3 bet: you win \$3 with probability of 0.999999 or you lose \$1,999,997 with probability 0.000001. The \$3 bet has consequences that you might have to give us almost two million dollars. Here is an example of the \$3 bet. We have a pot containing a million quarters. They are all Arizona quarters, except for one California quarter. We will put a hand into the pot and pull out one-quarter. If it is an Arizona quarter, you win \$3. But if it is the California quarter, you owe us almost two million dollars!

Which of these three wagers would you prefer to take? Most engineers prefer the \$2 bet. Very few people choose the \$3 bet, because they fear the possibility of a great loss. However, all three of these bets have the same expected value of \$1.

A neophyte was watching an NCCA basketball game and his roommate walked in and asked, “Who’s winning?” The TV watcher replied, “The game is nearly over and we are losing 69 to 65.” That is not the way a basketball aficionado would answer. The aficionado would respond, “We are down by four with two minutes left.” While watching a game, an aficionado does not keep the score in his head. He just remembers by how many points we are up or down. This is in keeping with the reference point concept of Fig. 2.8. Furthering the comparison, being down by four points is more saddening than being up by four would be gladdening.

It is easy to construct utility curves as in Fig. 2.8 if the value is in consistent units such as dollars, as we have just shown. But what if the **value** is in different units? Table 2.1 shows data from the renewable energy trade-off study in Chap. 5 of this textbook. It compares several criteria for many alternatives.

It is not possible to plot data like these on a graph like Fig. 2.8. But fortunately, there is a convenient metric that will work, the power-to-price ratio. This ratio

Table 2.1 Rated power and price for several alternative renewable energy systems of Chap. 5

Criteria	Sun electronics PV	DM solar PV	Jacobs Wind turbine	Bergey wind power	Abundant renewable energy	Sky stream	Nordtank 65
Rated power (kW)	10.2	10.4	20	10	10	2.4	65
Purchase price (\$)	\$34,000	\$34,000	\$55,000	\$29,500	\$50,000	\$14,000	\$62,000

PV means photovoltaic solar panels

Table 2.2 Power-to-price ratio for several alternative renewable energy systems

Criteria	Sun electronics PV	DM solar PV	Jacobs wind turbine	Bergey wind power	Abundant renewable energy	Sky stream	Nordtank 65
Rated power (kW)	10.2	10.4	20	10	10	2.4	65
Purchase price (\$)	\$34,000	\$34,000	\$55,000	\$29,500	\$50,000	\$14,000	\$62,000
Power-to-price ratio (W/\$)	\$0.30	\$0.31	\$0.36	\$0.34	\$0.20	\$0.17	\$1.05

shows saturation. The Nordtank system has a high ratio, but it did not generate three times the excitement of the PV systems, because of this saturation (Table 2.2).

Figure 2.8 shows saturation at the left and right, a non-zero reference point and that gains and losses are not weighted equally, as the following example demonstrates.

Situation 1. Assume that you are offered a choice between

1. A sure gain of \$100 or
2. A 50 % chance to win \$200 and a 50 % chance to win \$0

Which would you choose? Most people (75 %) take the \$100.

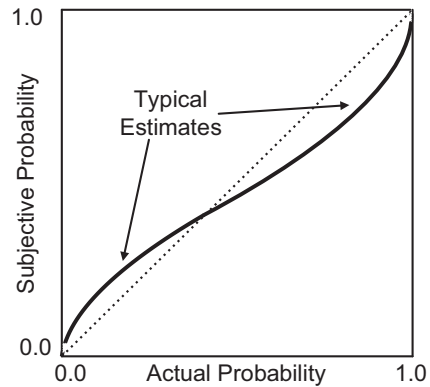
Situation 2. Assume that you are offered a choice between

1. A sure loss of \$100 or
2. A 50 % chance to lose \$200 and a 50 % chance to lose \$0

Which would you choose? Most people (75 %) choose the gamble, because they want to escape a loss.

People prefer to avoid losses more than they prefer to get gains.

Fig. 2.9 Subjective probability assessment compared to actual probabilities, Tversky and Kahneman [11]



2.2.2 Subjective Probability

Prospect theory describes subjective evaluation of probabilities according to the experimentally obtained curve in Fig. 2.9 [11]. Subjectively, small probabilities are overestimated and large probabilities are underestimated.

People tend to overestimate the probabilities of low-likelihood events, such as being killed by a terrorist, or dying in an airplane crash, and underestimate the probabilities of high-likelihood events, such as adults dying of cardiovascular disease. The existence of state lotteries depends on such overestimation of small probabilities. On the right side of this figure, the probability of a brand new car starting every time is very close to 1.0. But people still carry jumper cables in the trunk and routinely buy memberships in AAA. This figure will go in the upper-right corner of Fig. 2.7.

Animals also exhibit tendencies of overestimating low probabilities while not distinguishing much between intermediate probabilities. For example, rats show this pattern [18].

For events where the actual probabilities are between 0.1 and 0.4, humans typically overestimate the probabilities. Moreover, if the event is said to have high severity, then humans overestimate the probability even more [19].

2.2.2.1 Context Dependence (Framing)

People exhibit context dependence: whether A is chosen more often than B can depend on the presence of an irrelevant third choice C, which is dominated and is never chosen [20]. Context dependence means people compare choices within a set rather than assigning separate numerical utilities. Honeybees exhibit the same pattern [21]. Animals also exhibit risk aversion, as will be discussed in Chap. 6.

Next, we consider an example of erroneous estimation of probabilities. Bill is an intelligent, well-organized individual who carries a laptop and dresses conservatively. What is his most likely major in college, Arts and Humanities or

Engineering? A bit of background might help here. In 2009, there were 1,410,000 students majoring in Engineering in American colleges, whereas there were 4,916,000 majoring in Arts and Humanities. Therefore, regardless of what you think of Bill, he is most likely an Arts and Humanities major.

2.2.2.2 Monty Hall Paradox

Humans are not good at estimating probabilities. This fact is amply illustrated by the Monty Hall Paradox, invented by Martin Gardner. This paradox was first published in his *Scientific American* column in 1959. It is called the Monty Hall paradox because of its resemblance to the TV show *Let's Make a Deal*. This version comes from Massimo Piattelli-Palmarini [6].

Suppose that we are running a game that we can repeat hundreds of times. Resting on a table in front of us are a stack of ten-dollar bills and three identical boxes (Fig. 2.10). You, the reader, are the subject. Here are the rules for each game. You leave the room and while you are out, we place a ten-dollar bill in one of the three boxes. Then we close the lids on all the boxes. We know which box contains the ten-dollar bill, but you do not. Next, we invite you back into the room. You have to guess which box contains the money. If you guess correctly, you get to keep the ten-dollar bill. Each game is divided into two phases. In the first phase, you point to your choice. You cannot open, lift, weigh, shake, or manipulate the boxes in any fashion. The boxes remain resolutely closed. After you make your choice, we open one of the two remaining boxes. Having seen one empty box (the one that we just opened) you now see two closed boxes, one of which contains the ten-dollar bill. Now here is your decision-making problem. Are you better off sticking to your original choice or switching? Many people say it makes no difference. There are two boxes and one contains a ten-dollar bill. Therefore, your chances of winning are 50/50. Almost all people refuse to switch, which is possibly explained by the endowment effect or the status quo bias wherein people prefer to stick with what they have. However, the laws of probability say that you *should* switch. The box you originally chose has, and always will have, a one-third probability of containing the ten-dollar bill. The other two, combined, have a two-thirds probability of containing the ten-dollar bill. But at the moment when we open an empty box



Fig. 2.10 Boxes for the Monty Hall Paradox

(we always open an empty box because we know where the ten-dollar bill is), then the other one alone will have a two-thirds probability of containing the ten-dollar bill. Therefore, your best strategy is to *always* switch! This is a difficult problem, because humans tend to struggle with probabilities.

2.2.3 Subjective Expected Utility

Subjective expected utility, the lower-right quadrant of Fig. 2.7, combines two subjective concepts: utility (subjective value) and subjective probability [22]. Utility is a subjective measure of the worth of an object. Subjective probability is the person’s assessment of the frequency or likelihood of the event occurring. The subjective expected utility is the expected value of the product of the utility times the subjective probability. Subjective expected utility theory models human decision-making as *maximizing subjective expected utility*: (1) maximizing, because people choose the set of alternatives with the highest total utility, (2) subjective, because the choice depends on the decision maker’s values and preferences, not on reality (e.g., advertising improves subjective perceptions of a product without improving the product), and (3) expected, because the expected value is used. This is called prospect theory: it is a first-order descriptive model of human decision-making.

Now, with a reasonable understanding of the key differences between objective and subjective values and probabilities, we can apply prospect theory to the expected value model of Fig. 2.7 and obtain the descriptive model of Fig. 2.11.

The upper-left corner is rational behavior, represented by the ideal Expected Value (represented by the big capital E and the big capital V). The upper-right

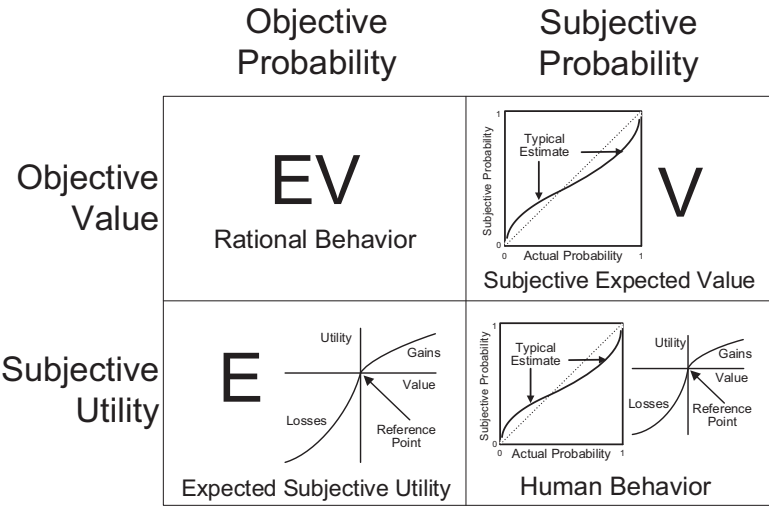


Fig. 2.11 Prospect theory model for human decision-making from Smith [14]

corner illustrates that humans cannot compute expected values, because they are poor at estimating probabilities. Therefore, instead of capital E, for expected value, we insert the human subjective estimate graph, which is then applied to the objective Value (capital V). In the lower-left corner, we apply the Expected value (capital E) to the human's subjective utility, which is represented by the graph of utility versus value. Finally, in the lower-right corner, instead of the expected value, we use the human estimated probability and instead of the objective value, we use the human subjective utility. Thus, the lower-right corner shows actual human behavior whereas the upper-left corner shows ideal rational behavior.

2.2.4 Implications

In the preceding paragraphs, we have reviewed the theoretical foundations of decision-making and human limitations in estimating probabilities. At this point, it is worth asking what conclusions we can draw from these findings. Upon examining human decision-making and expected decision practices, the presence of cognitive biases—even in extensively vetted analyses—can never be ruled out [1, 23]. This is the contention of the economic school of heuristics and biases, which produced prospect theory [24], a theory that describes how people respond to choices under risk and uncertainty. Innate human biases, and external circumstances, such as the framing or context of a question, can compromise decisions. It is important to note that subjects maintain a strong sense that they are acting rationally even when they are exhibiting these biases. Piattelli-Palmarini, in his book *Inevitable Illusions* [6], introduces this subject as follows:

The current term for these biases is “cognitive” illusions, to indicate that they exist quite apart from any subjective, emotional illusion and from any other such habitual, classical, irrational distortion by a particular subject. The pages that follow provide ample documentation, and contain suggestions as to how we may take urgent and sensible precautions against these illusions.

It never ceases to surprise me that, more or less 20 years after these illusions were first discovered, and after dozens of books and hundreds of articles have been printed on the subject of cognitive illusions, almost no one except for a select circle of specialists seems to have taken this discovery seriously [6, p. x].

In simple and basic fashion, this book proposes to set out the recent scientific discovery of an unconscious. Not the unconscious or subconscious explored by psychoanalysis, but one that *always and unbeknownst to us* involves the cognitive; that is, the world of reason, of judgment, of the choices to be made among different opportunities, of the difference between what we consider probable and what we consider unlikely [6, p. 1].

Because trade-off studies and risk analyses play such a vital role in decision-making, we reexamine the components of both with the intent of identifying how biases and illusions are introduced in subtle ways in each. In Chaps. 5 and 6, the

elements of trade-off studies and risk analyses are examined together with common biases and illusions that may unconsciously and inadvertently affect what is presumed to be rational decision-making.

2.2.5 What Is Risk?

The utility of an item includes both subjectively assessed value and the assessor’s attitude toward risk. Engineers use the word risk to evaluate and manage bad things that could happen. Risk is quantified by the frequency (or probability) of occurrence times the severity of the consequences. However, in economics and psychology uncertainty risk is defined as the variance of the expected value, which is uncertainty [18].

Table 2.3 explains three bets: A, B, and C. The p ’s are the probabilities, the x ’s are the outcomes, μ ’s are the means, and σ ’s are the variances. This table shows, for example, that half the time bet C pays \$1 and the other half of the time it pays \$19. Thus, this bet has an expected value of \$10 and a variance of \$9. This is a comparatively big variance, so the uncertainty risk is said to be high. Most people prefer bet A, the certain bet.

In choosing between alternatives that are identical with respect to quantity and quality of the reinforcement (expected value, μ), but differ with respect to probability of reinforcement, humans, rats [25], bumblebees [26], honeybees [21], and gray jays [21] prefer the alternative with the lower variance.

To avoid the confusion caused by system engineers and decision theorists using the word *risk* in two different ways, we will refrain from using the word “risk” in this section and instead use ambiguity, uncertainty, and hazards [18].

2.2.5.1 Ambiguity, Uncertainty, and Hazards

A few years ago, a wild fire was heading in the direction of a residential home. The residents packed their car with their valuables, but had no room to save everything. Consequently, they laid their wine bottles in the swimming pool. They put the dog in the car and drove off. When they came back, the house was burned to the ground, but the swimming pool survived. However, the labels were soaked off of the wine bottles. Later, the residents, feeling quite fortunate, invited you to a dinner party to celebrate their safe return. They decided to serve mushrooms that they had picked

Table 2.3 Mean and variance of bets A, B, and C

Name of bet	p_1	x_1	p_2	x_2	μ	σ	Uncertainty, risk
A	1.0	\$10			\$10	\$0	None
B	0.5	\$5	0.5	\$15	\$10	\$5	Medium
C	0.5	\$1	0.5	\$19	\$10	\$9	High

in the forest, while they were waiting for the fire to subside. There may be some hazard here, because they are not mushroom experts. To accompany dinner, they decided to drink some of their saved wine. There is some uncertainty here, because while you know that none of their wines are cheap, you also know that some are much better than others. Finally, they announce that their sauce for the mushrooms contains saffron and truffles. This produces ambiguity, because you most likely do not know what these ingredients taste like. In light of the foregoing, how would you respond to each of these choices?

Hazard: Would you prefer their forest picked mushrooms or chanterelle mushrooms from the grocery store?

Uncertainty: Would you prefer one of their wines or a Duckhorn Vineyard merlot?

Ambiguity: Would you prefer their saffron and oyster sauce or marinara sauce?

Decisions involving these three concepts are believed to be made in different parts of the brain. The Ellsberg paradox is used to explain the difference between ambiguity and uncertainty [27]. The experimenters gave their subjects a deck of cards and told them it contained 10 red cards and 10 blue cards (the uncertain deck). Another deck had 20 cards, either red or blue, but the percentage of each was unknown (the ambiguous deck). The subjects could take their chances drawing a card from the uncertain deck: if the card were the color that they predicted they won \$10, else they got nothing. Or instead of picking a card, they could just take \$3 and quit. Most people picked a card. Then their subjects were offered the same bets with the ambiguous deck. Most people took the \$3, thus avoiding the ambiguous decision. The experimenters recorded functional magnetic resonance images (fMRI) of their brains while their subjects made these decisions. While contemplating a decision about the uncertain deck, the dorsal striatum showed the most activity and when contemplating a decision about the ambiguous deck the amygdala and the orbitofrontal cortex showed the most activity. Ambiguity, uncertainty, and hazards are three similar but, in fact, different things. Interestingly, people, to different degrees, prefer to avoid all three.

2.2.6 Confirmation Bias

Arguably, the most important principle in the fallibility of human decision-making is confirmation bias [1, 23]. Humans hear what they want to hear and reject what they do not want to hear. Humans filter-out information that contradicts their preconceived notions, and remember things that reinforce their beliefs. Confirmation bias causes decision makers to actively seek out and assign more weight to evidence that confirms their hypotheses and ignore or under weigh evidence that could disconfirm their hypotheses. For example, mothers emphasize good deeds of their children and de-emphasize their bad deeds. This is why we often hear the mother of a terrorist crying out, “My boy is innocent. He could never have killed all those people.” People who think that they have perfect memory and perfect recall

tend to ignore instances when they forgot something and tend to secure in long-term memory instances when they (but not others) correctly recalled events and facts. Senior citizens often believe that they are good drivers despite instances that show that they have poor vision and slow reflexes. Thirty years ago, most smokers were in denial about the hazards of smoking. Some people say, "There must be a storm coming, because my arthritic joints are hurting."

Social media is making this worse. Not only do you filter what you believe, but also Facebook filters what you see. They present to you things from the friends you care about. These friends are probably ideologically similar to you, which accentuates the filtering process.

Nickerson [28] reported many common instances of confirmation bias. In one, the subjects were given a triplet such as (2, 4, 6) and were asked to imagine the rule that was used to generate the triplet and then try to prove or disprove that rule. After each of their guesses, they were told if they were right or wrong. For example, if the subject's mental model for the rule was "successive even numbers," they might guess (10, 12, 14) or (20, 22, 24), triplets that would confirm their mental model, but seldom would they try (1, 3, 5) or (2, 4, 8), triplets that might disprove their mental model. He also presented another example of confirmation bias, witches.

The execution of 40,000 suspected witches in seventeenth-century England is a particularly horrific case of confirmation bias functioning in an extreme way at the societal level. From the perspective of the people of the time, belief in witchcraft was perfectly natural and sorcery was widely viewed as the reason for ills and troubles that could not otherwise be explained. In one test of being a witch, the mob would throw the suspect into a river, if the suspect floated, it was proof that she was a witch and she was executed.

Until the nineteenth century, physicians often did more harm than good because of confirmation bias. Virtually anything that could be dreamt up for the treatment of disease was tried and, once tried, lasted decades or even centuries before being given up. It was, in retrospect, the most frivolous and irresponsible kind of human experimentation. They used blood-letting, purging, infusions of plant extracts and solutions of metals and every conceivable diet including total fasting, most of these were based on no scientific evidence. How could such ineffective measures continue for decades or centuries without their ineffectiveness being discovered? Probably, because sometimes patients got better when they were treated, sometimes they did not and sometimes they got better when they were not treated at all. Peoples' beliefs about the efficacy of specific treatments seem to have been influenced more strongly by those instances in which treatment was followed by recovery or those instances in which recovery occurred spontaneously, than by those instances in which there was no recovery. A tendency to focus on positive cases could explain why the discovery that diseases have a natural history and people often recover from them with or without treatment was not made until much later.

In the middle of the nineteenth century, a Hungarian physician reasoned that so many mothers got infections when delivering babies in a hospital was that the doctors and nurses did not wash their hands before delivering the baby.

Preconceived notions in the medical community allowed doctors to reject his advice for decades.

Most people react to news articles with confirmation bias. If a liberal reads a news story about a scientific study that showed how effective it was to give money to poor people. He might think, “That’s interesting. I’ll remember that.” However, if one of these liberals reads about a new study showing that giving people money when they are unemployed just makes their lives worse. Then he might start looking for flaws in the study. If a person has a long-felt belief that the income gap between the rich and the poor in America is too large and is growing fast, then a new study that challenges this belief might be met with hostility and resistance. However, if that person readily accepts a study that reinforces his beliefs, that is confirmation bias.

People do not think like scientists: they think like lawyers. They form an opinion and then emphasize only evidence that backs up that opinion.

2.2.7 *Severity Amplifiers*

Interpersonal variability in evaluating the seriousness of a situation depends on the framing. That is, the circumstances surrounding the event will affect how a person responds to it [1, 2, 29–31]. An evaluation may depend on factors such as how the criterion affects that person, whether that person voluntarily exposed himself to the risk, how well that person understands the alternative technologies and the severity of the results. The following are severity amplifiers: lack of control, lack of choice, lack of trust, lack of warning, lack of understanding, manmade, newness, dreadfulness, personalization, ego, recallability, vividness, uncertainty, and immediacy.

Here are some examples of these severity amplifiers: *Lack of control*: a man may be less afraid driving his car up a steep mountain road at 55 mph than having his wife drive him to school at 35 mph. *Lack of choice*: we are more afraid of risks that are imposed on us than those we take by choice. *Lack of trust*: we are less afraid listening to the head of the Center for Disease Control explain anthrax than listening to a politician explain it. *Lack of warning*: people dread earthquakes more than hurricanes, because hurricanes give hours or days of warning. People in California follow strict earthquake regulations in new construction. People in New Orleans seem to ignore the possibility of hurricanes. *Lack of understanding*: we are more afraid of ionizing radiation from a nuclear reactor than of infrared radiation from the sun. In the 1980s engineers invented nuclear magnetic resonance imaging (NMRI). When the medical community adopted it, they renamed it magnetic resonance imaging (MRI). They dropped the adjective nuclear. *Manmade*: we are more afraid of nuclear power accidents than solar radiation. *Newness*: we are more afraid when a new disease (e.g., swine flu, SARs, bird flu, Ebola and Zika) first shows up in our area than after it has been around a few years. *Dreadfulness*: we are more afraid of dying in an airplane crash than of dying in a hospital bed from heart disease. *Fear*: if a friend tells you that, a 6-ft rattlesnake struck at him, how long do

you think the snake was? We suspect 3 ft. But, of course, the length of the snake is irrelevant to the harm it could cause. *Personalization*: a risk threatening me, it is worse than that same risk threatening you. *Ego*: a risk threatening my reputation is more serious than one threatening the environment. *Recallability*: we are more afraid of cancer if a friend has recently died of cancer. We are more afraid of traffic accidents if we have just observed one. *Vividness of description*: an Edgar Allen Poe story read by Vincent Price will be scarier, than one that I read. *Ambiguity or uncertainty*: most people would rather hear their ophthalmologist say, “You have a detached retina. We will operate tonight.” than, “You might have a detaching vitreous, or it could be a detaching retina, or maybe its cancer. We will let you know the results of the tests.” *Immediacy*: a famous astrophysicist was explaining a model for the life cycle of the universe. He said, “In a billion years our sun will run out of fuel and the earth will become a frozen rock.” A man who was slightly dozing awoke suddenly, jumped up, and excitedly exclaimed, “What did you just say?” The astrophysicist repeated, “In a billion years our sun will run out of fuel and the earth will become a frozen rock.” With a sigh of relief, the disturbed man said, “Oh thank God. I though you said in a *million* years.”

2.2.8 Framing

We have mentioned *framing* several times in this section. With Fig. 2.8 we wrote that utility is considered not in an absolute sense (from zero), but rather subjectively from a reference point established by the Decision Maker’s (DM) perspective and wealth before the decision, which is his frame of reference. Utility is also affected by whether the event is phrased as a gain or a loss. We wrote that framing (the context of a question) could affect his decision. The section on Severity Amplifiers stated that interpersonal variability in evaluating the seriousness of a situation depends on framing. That is, the circumstances surrounding the event will affect how a DM responds to it. An evaluation may depend on factors such as how the criterion affects that DM, whether that DM voluntarily exposed himself to the risk, how well that DM understands the alternative technologies and the severity of the results. Then we explained over a dozen more severity amplifiers that would affect the framing of a problem.

In contrast to defining framing in passing, as we have done so far, we will now explain framing directly [32]. The DM has a vision, a mission, values, morals, ethics, beliefs, evaluation criteria, and standards for how things should be and how people ought to behave. Collectively these are called *principles*. They are what the DM, the group, or the organization stands for. They limit the goals that are worthy of pursuing and acceptable ways of pursuing these goals. These principles are difficult to articulate, but they powerfully influence the DM’s behavior. They are the foundation of the DM’s decisions and goals; actions that contradict them will be unacceptable. The utility of the outcomes of decisions derives from the degree to which these decisions conform to and enhance the DM’s principles.

Goals are what the DM wants to accomplish. The goals are dictated by the principles, the problem, the problem statement, opportunities, desires, competitive issues, or gaps encountered in the environment. Goals might seed more principles. Goals should be SMART: specific, measurable, achievable, realistic, and time-bound.

The DM has *plans* for implementing the goals. Each goal has an accompanying plan. Each plan has two aspects: (1) tactics are the concrete behavioral aspects that deal with local environmental conditions and (2) forecasts are the anticipation of the future that provide a scenario for forecasting what might result if the tactics are successful. The plans for the various goals must be coordinated so that they do not interfere with each other and so that the DM can maintain an orderly pursuit of the goals. The plans are also fed back to the principles; therefore, they might foment more principles.

Framing means embedding observed events into a context that gives them meaning. Events do not occur in isolation; the DM usually has an idea about what led up to them. This knowledge supplies the context, the ongoing story that gives coherence to experiences, without which things would appear random and unrelated. A frame of reference consists of the principles, goals, and plans that are deemed relevant to the decision at hand and that fixes the set of principles that influence that decision.

The DM uses contextual information to probe his or her memory. If the probe locates a contextual memory that has similar features to the current context, then the current context is said to be recognized. Recognition defines which principles, goals, and plans are relevant to the current context and provides information about the goals and plans that were previously pursued in this context. If a similar goal is being pursued this time, then the plan that was used before may be used again.

In summary, framing means describing all aspects of the problem, the problem statement, and the DM's mind that will affect decisions.

2.2.9 *Framing Is the Overarching Process*

Confirmation bias, severity amplifiers, conflict of interest, and many other reasoning mistakes may be subsets of bad framing. In all of these, the secret to success is creating a frame of reference with just the right amount of detail.

In previous centuries, physicians often did more harm than good. They used bloodletting, purging, infusions of plant extracts, injections of metal solutions, and numerous other horrible practices. How could such futile medical care have continued for decades or centuries without its ineffectiveness being discovered? Perhaps because the treatment decisions were not framed properly. When patients recovered, that was remembered. But when they got worse, it was forgotten. The frame of reference contained only successes: this is confirmation bias.

The two dozen severity amplifiers given in a section above, all showed one basic decision being made within two frames of reference.

In March 1945, General Patton sent an armored column behind German lines to rescue POWs in OFLAG XIII-B, near Hammelburg. The mission was a failure. General Eisenhower reprimanded Patton for ordering this operation. Patton said that his mistake was sending a force too small to perform the mission: “I can say this, that throughout the campaign in Europe I know of no error I made except that of failing to send a combat command to take Hammelburg.” The complete frame of reference shows that Patton may have had a conflict of interest in deciding to initiate that mission, because his son-in-law was a POW in that camp.

Imagine standing beside railroad tracks. You see a train coming down the tracks heading for a group of small children. You are right next to a switch that can reroute the train down a siding, where an old woman has fallen on the tracks. Do you throw the switch? If you don’t, many children will die, but you would not have been the cause of their deaths. However, if you throw the switch, the old woman will die and you would have been the *direct* cause, because *your action* caused her death? Do you think that this could be the reason why the pilot of jet fighter does not fire the missile? Instead, he sends a launch signal to Fire Control and it launches the missile. What if the old woman was your mother? Would that change your frame of reference?

Should you always tell the truth? It depends on your frame of reference. Immanuel Kant invented the following dilemma. Suppose an honorable friend says to you, “Quick hide me. Someone is trying to kill me.” Then a murderous looking man with a gun shouts at you, “Is that scoundrel hiding in your house? I swear just saw him slither in.” Should you lie to protect the innocent man, or should you tell the truth?

All of these reasoning mistakes can be ameliorated by a better description of the frame of reference. We have often said that the best answer most systems engineering questions is, “It depends.” Well, it depends on what? It depends on the frame of reference.

2.2.10 Section Summary

In this section, we have discussed salient differences between perfect (rational) behavior and actual human behavior. In Chaps. 5 and 6, we will show how trade-off studies and risk analyses can help move an individual toward making decisions that are more rational (upper-left quarter of Fig. 2.11).

Some day you may find yourself helping a decision maker make informed and defensible decisions. We know that when viewed in formal terms this is a difficult, iterative task. It entails discovering the decision maker’s values, principles, importance weights, scoring functions, and preferred combining functions. You need to get into the head of the decision maker to discover his or her preferences and values. Also, different people have different personality types. The Myers-Briggs model is

one way of describing these personality types. *Sensory-Thinking-Judging* people are likely to appreciate the decision-making concepts that are in this book. *Intuitive-Feeling* people might not feel that way. Nevertheless, concepts such as those presented in the preceding paragraphs might help you to understand the values and preferences of the decision maker that you are assisting.

In addition to human foibles described by prospect theory, there are several other factors that can adversely affect human decisions. These include corporate culture, framing of the decision, information displayed, wording of questions, context, the decision itself, the effort required to make the decision, the difficulty in making the decision, the time available to make the decision, needed decision accuracy, cost of the decision, likelihood of regret and, finally, the decision maker's values, personality types, risk averseness, biases, illusions, and use of heuristics.

2.2.11 Homework Problems

2.2.11.1 Prospect Theory 1

Tversky and Kahneman ran an experiment concerning a hypothetical outbreak of a new unusual disease that was expected to kill 600 people. Their subjects were divided into two groups and each was given two programs to ponder.

One group of subjects were told that

If Program A were adopted, 200 people would be saved.

If Program B were adopted, there would be a $1/3$ probability that 600 people would be saved, and $2/3$ probability that no people would be saved.

In this group, 72 % of the subjects choose Program A and 28 % choose Program B.

A second group of subjects were told that

If Program C were adopted, 400 people would die.

If Program D were adopted, there would be a $1/3$ probability that nobody would die, and $2/3$ probability that 600 people would die.

In this group, 22 % of the subjects choose Program C and 78 % choose Program D.

Note: The difference between 72 % and 78 % is not important. What is important is that one group chose Program A by a 3-to-1 margin and that the other group choose Program D by a 3-to-1 margin.

Compute the expected value for each of these four programs, assuming that value is determined by the number of lives saved.

Try using the prospect theory graph of Fig. 2.8 to compare the various options. Let us assume that the following data were derived for their experimental subjects.

Specific numbers for a curve like Fig. 2.8.

Objective value	Subjective utility
−600	−6
−400	−4.5
\$0	\$0
+200	+1.5
+600	+3.25

Now calculate the subjective utilities:
Does using subjective utility postulated by prospect theory explain the way people respond to these various options?

2.2.11.2 Prospect Theory 2

When our subject (S) is tasked with a decision, the problem will be set within a frame of reference containing a reference point. This allows S to classify the results of the decision as either gains or losses. S then forms the subjective expected utility, which equals the subjective utility times the subjective probability. The subjective utility is formed using a value function similar to Fig. 2.8 and the subjective probability is formed using a weighting function similar to Fig. 2.9.

Here is an example. S owns a house on the Florida coast valued at one million dollars. He is trying to decide whether or not to buy a hurricane insurance policy costing \$500,000 per year. The weather service estimates a 50 % chance that a hurricane will destroy his house this year. Under the expected value criterion, he should feel neutral about buying the policy, because the cost of the insurance is monetarily equal to the potential loss. However, under prospect theory, we first form a frame of reference in which we will consider the decision; we will use his current state as the reference point. The data in the following table are for this frame and Fig. 2.8.

Specific numbers for a curve like Fig. 2.8.

Objective value	Subjective utility
−\$100,000	−\$500,000
−\$500,000	−\$400,00
−\$10,000	−\$30,000
\$0	\$0
+\$500,000	+\$300,000
+\$1,000,000	+\$350,000

This table shows that a \$1,000,000 actual loss subjectively *feels* like a \$500,000 loss, and a \$500,000 actual loss subjectively feels like a \$400,000 loss.

The data in the following table show his subjective probabilities versus the actual probabilities. This table shows, for example, that an actual 0.5 probability feels like a 0.4 probability.

Specific numbers for a curve like Fig. 2.9.

Actual probabilities	Subjective probabilities
0.01	0.1
0.5	0.4

To bring it all together, S’s choice is a \$400,000 subjective loss if he buys the insurance, versus a 0.4 subjective probability of a \$500,000 subjective loss if he does not. Buying insurance has a subjective expected utility of $-\$400,000$, not buying insurance has a subjective expected utility 0.4 times \$500,000 which is $-\$200,000$. So S rejects the insurance.

Now, let us assume that S owns a one million dollar house in New Hampshire, where there is only a 1 % chance of a hurricane destroying his house. But a hurricane insurance policy only cost \$10,000 in New Hampshire. Should he buy insurance?

Suddenly, S receives a stupendously lucky break! He receives an e-mail that tells him that he is the lucky winner of either \$500,000 in cash or a 50 % chance on a one million dollar house in New Orleans. Which should he choose? To redeem his prize he should provide by return e-mail his preference, his bank account number (so that they can deposit the money in his account), and his SSN (because they must withhold federal income tax). How would *you* reply?

2.2.11.3 Decision Mistakes

Make a list of the best batters in major league baseball since 1900? What mistakes might you have made in making this decision?

2.2.11.4 Estimating Probabilities and Utilities

For an average major league batter, in a single plate appearance, what do *you think* is the probability of him getting a homerun (HR), a double (2B), a single (1B), a run batted in (RBI), a base on balls (BB), reaching base on error (ROE), a strikeout (SO), and grounding into a double play (GDP)? At first, do not look these up on the Internet, just give your best estimates. Put your estimates in the middle column of Table 2.4. After you see our solutions, record whether you over- or underestimated the probabilities.

Now assume that there are batters on first and second base. Use runs batted in (RBI) as the input objective value. Calculate the utility (subjective worth) of a homerun (HR), a double (2B), a single (1B), a base on balls (BB), reaching base on error (ROE), a strikeout (SO), and grounding into a double play (GDP)? Put your estimates in the right column of Table 2.4. For a reference point, use reaching base safely on an error. For this situation, a HR should produce three RBIs. A stand-up

Table 2.4 Subjective probability and utility estimates

Batting outcomes	Subjective probability estimated by a knowledgeable human, events per at bat (AB)	Subjective worth (utility) assessed by a knowledgeable human
Homerun (HR)		
Double (2B)		
Single (1B)		
Bat in a run (RBI)		
Base on balls (BB)		
Reach base on error (ROE)		
Strikeout (SO)		
Ground into double play (GDP)		

double should produce two RBIs plus leave a man in scoring position. A single should produce one RBI plus leave two men on base. On average, each team scores four runs and suffers 27 outs in a game.

2.2.11.5 Rewrite This Statement

We have a surgical procedure that will cure your problem. Statistically 1 % of the people who undergo this surgery die. Would you like to have this surgery?

2.2.11.6 Confirmation Bias

Suppose that you are given a triplet such as (1, 1, 2) and are asked to hypothesize the rule that generated this triplet. Create some test triplets that will prove or disprove your hypothesis. Assume that after each of your guesses, you will be told if your triplet could have been generated by the rule.

**2.3 Section 18. Potential Mental Mistakes
in Trade-off Studies**

Studies in Judgment and Decision-Making, Cognitive Science and Behavioral Economics can be used to shed light on various aspects of requirements analysis, trade-off studies, and risk assessment. Of course, since many experiments in these fields were designed to reveal truths about human choice at a basic level, they do not address high-level cognitive decisions involved in requirements discovery, trade-off studies, and risk analyses. To shed light on this point, the following sections compare the elements of the experiments at an abstract level. This section

deals primarily with trade-off studies and secondarily with requirements discovery and risk analysis. This section is based on Smith, Son, Piattelli-Palmarini, and Bahill [33, 34].

This decision-making literature uses terms such as biases, cognitive illusions, emotions, fallacies, attribute substitution, simplifying heuristics, fear of regret, psychological traps, and paradoxes. In this section, when we refer to specific experiments we use the terminology used in the basic research papers. However, in showing how these factors could adversely affect a trade-off study, we call all of these factors by the collective term “mental mistakes.”

Humans often make mental mistakes when conducting requirements analysis, trade-off studies, and risk assessment. Smith [14] extracted seven dozen mental mistakes including heuristics, biases, representativeness, anchoring, base-rate neglect, the conjunction fallacy, cognitive illusions, emotions, fallacies, fear of regret, psychological traps, and paradoxes from the field of *behavioral economics* (Thaler’s memoir [32] summarizes this field nicely) and showed how they could induce mental mistakes in trade-off studies. Many of these are discussed in [6, 35–38].

We studied these mental mistakes and determined whether each one principally affects (1) magnitudes, such as evaluation data, weights, and probabilities or (2) textual descriptions, such as stating the problem, writing criteria, or proposing alternatives.

The next section describes these mental mistakes and offers recommendations for ameliorating their effects on the trade-off study components. Our research draws on existing, rigorous experimental results in the cognitive science literature, and provides a cautionary alert about the likelihood of large-scale occurrences of cognitive biases within trade-off studies. To this end, this work offers guidelines for the systems engineering community to consider when developing systems. The positive experimental identification of each bias—specifically within trade-off studies and trade-off study components—is not a goal generally pursued. Therefore, experimentation for all the biases in a trade-off study context can potentially take decades.

2.3.1 *Prospect Theory*

The seminal paper on cognitive biases and heuristics under uncertainty was authored by Tversky and Kahneman [39]. This work led to the creation of prospect theory [24]. Prospect theory breaks subjective decision-making into a preliminary screening stage and a secondary evaluation stage. In the screening stage, values are considered not in an absolute sense (from zero), but subjectively from a reference point established by the subject’s perspective and wealth status prior to making the decision. Please recall Fig. 2.8. In this stage, losses are weighted more heavily than gains. In the evaluation stage, a final value for every prospect (alternative) is calculated. Subsequent refinements to this theory, including subjective probability assessment, were published in Tversky and Kahneman [11], which was reprinted in

Tversky and Kahneman [40]. Kahneman won the Nobel Prize in Economics in 2002 “for having integrated insights from psychological research into economic science, especially concerning human judgment and decision-making under uncertainty” [41, 42].

Several heuristics and biases, notably representativeness, anchoring, base-rate neglect, and the conjunction fallacy are now considered by Kahneman to be instances of a super-heuristic called *attribute substitution*. Judgment is mediated by this heuristic when, without realizing its existence [43]

an individual assesses a specified target attribute of a judgment object by substituting another property of that object—the heuristic attribute—which comes more readily to mind. Many judgments are made by this process of *attribute substitution*. For an example, consider the well-known study by Strack, Martin, & Schwarz [44], in which college students answered a survey that included these two questions: How happy are you with your life in general? How many dates did you have last month? The correlation between the two questions was negligible when they occurred in the order shown, but it rose to 0.66 when the dating question was asked first [45, p. 53].

As we see clearly in this instance, the target attribute (happiness) is assessed by mapping the value of another attribute (number of dates last month) onto the target scale. This process of attribute substitution

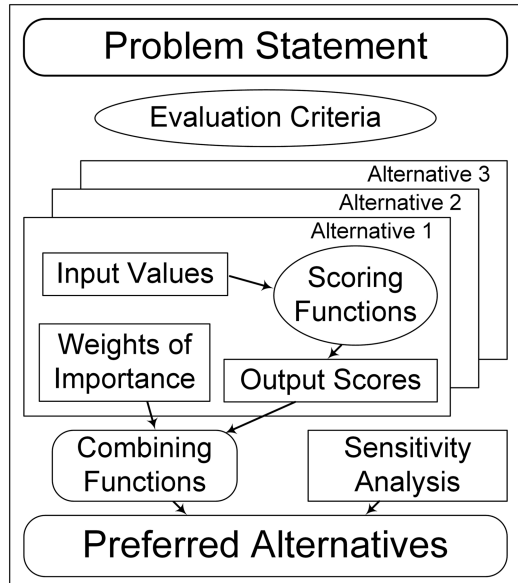
“will control judgment when these three conditions are satisfied: (1) the target attribute is relatively inaccessible (happiness); (2) a semantically and associatively related candidate attribute is highly accessible (number of dates last month); and (3) the substitution of the heuristic attribute in the judgment and the immediacy of the response is not rejected by the critical operations of” thoughtful thinking [45, p. 54].

Our goal is to recommend actions that will help people avoid making specific mental mistakes when conducting trade-off studies. Later we will consider mistakes that are specific to requirements discovery and risk analyses. Our intention is to help people in defining trade-off studies to choose among alternatives. We want people to have confidence in their decision. We also present arguments to convince people to validate their systems. These recommendations are the principal outputs of this research (Fig. 2.12).

The components of a trade-off study are:

- Problem statement
- Evaluation criteria
- Weights of importance
- Alternative solutions
- Evaluation data
- Scoring functions
- Normalized output scores
- Combining functions
- Preferred alternatives
- Sensitivity analyses

Fig. 2.12 Elements of a trade-off study



2.3.2 Problem Statement Mistakes

Problem statement errors can arise from a variety of mental mistakes such as

- Bad problem stating
- Incorrect phrasing
- Attribute substitution
- Political correctness
- Feeling invincible

Each of these sources is discussed next.

2.3.2.1 Bad Problem Stating

The problem of system design must be stated strictly in terms of functions and requirements, not in terms of a solution, or a class of solutions [46]. It is a serious mistake to state a problem in terms of a solution, instead of customer needs and expectations.

Recommendation: Question the customer to determine his or her values and real needs.

2.3.2.2 Incorrect Phrasing

The way a question is phrased can potentially influence the answer. With respect to the formulation of public policy, Kahneman and Ritov [47] showed their subjects (1) brief statements that looked like headlines and (2) proposed methods of intervention. Some subjects were asked to indicate their willingness to pay for the interventions by voluntary monetary contributions; other subjects were asked which intervention they would rather support.

Issue Mammals

Problem: Several Australian mammal species are nearly wiped out by hunters.

Intervention: Contribute money to a fund to provide a safe breeding area for these endangered species.

Issue Skin Cancer

Problem: Skin cancer from sun exposure is common among farm workers.

Intervention: Support free medical checkups for threatened groups.

On being asked how much money they would be willing to contribute, most subjects indicated that they would contribute more money to provide a safe breeding area for the Australian mammal species than they would to support free medical checkups for the threatened farm workers. However, when the subjects were asked which intervention they would support, they indicated that they would rather support free medical checkups for threatened workers.

Recommendation: Questions designed to elicit a value for a criterion should be tightly coupled to the criterion.

The way a question is phrased will determine, in large part, the answer one gets. When asked whether they would approve surgery in a hypothetical medical emergency, many more people accepted surgery when the chance of survival was given as 99 % than when the chance of death was given as 1 %. In a supermarket, assume you see two packages of ground beef. One is labeled, “80 % fat free.” The other is labeled, “Contains 20 % fat.” Which one do you buy?

2.3.2.3 Attribute Substitution

Attribute substitution occurs when a subject, while assessing an attribute, substitutes a related attribute that comes more readily to mind. In effect, “people who are confronted with a difficult question sometimes answer an easier one instead” [42, p. 707]. When confronted with a choice among alternatives that should properly be decided by a full trade-off study, there is a strong tendency to substitute a seemingly equivalent yet much simpler decision question in place of the trade-off study process.

Here is one more example. Suppose that you want to measure the salinity of water for drinking or irrigation. You could measure it directly or you could use

attribution substitution and instead measure the electrical conductivity. This usually works very well and is a lot cheaper. But as the system progresses we might learn that some ions are more dangerous than others. Then we would have to stop substituting and actually measure the amount of chloride, Mg^{3+} , and HCO_3^- individually and electrical conductivity would not be a good proxy.

Recommendation: Sponsors of trade-off studies should recognize that a premature reduction of the trade-off space invariably leads to a simpler decision question. While this is a common heuristic that is inadvertently applied, it fails to address the original multi-objective decision.

2.3.2.4 Political Correctness

Fear of being politically incorrect causes many top-level decision makers to be reluctant to state the problem clearly and concisely.

2.3.2.5 Feeling Invincible

Teen-agers, especially boys, are notorious for thinking that they are indestructible and immune to adversity. I won't get caught. I can't get hurt. I will avoid car accidents. I won't cause an unwanted pregnancy. I won't get sexually transmitted disease. I don't have to back up my hard drive, because my computer won't crash. And, They can't do that to me. In 1912, the White Star line said that the Titanic was "unsinkable." This mental mistake is particularly insidious when performing risk analyses.

Recommendation: Decision makers must learn to and have the freedom to question all assumptions (no sacred cows!).

It is worth noting that codebreakers have been systematically making and breaking codes for more than 600 years. During WWII, the Allied commanding generals often had copies of Hitler's battle orders before the German generals did. Yet, the Germans were absolutely certain that no one had broken their Enigma codes.

When President Franklin Delano Roosevelt (FDR) was campaigning for his first term as president, he made a memorable speech in Pittsburgh in which he promised that he would slash government spending and balance the budget. Returning to that city in 1936, seeking reelection after 4 years of record government outlays, he asked his top speechwriter, Sam Rosenman, how he should spin this reversal. Rosenman replied, be bold, "Deny you were ever in Pittsburgh" [48].

2.3.3 *Evaluation Criteria Mistakes*

Evaluation criteria mistakes fall into three main categories:

- Dependent criteria
- Relying on personal experience
- Forer Effect

Each category is discussed next.

2.3.3.1 **Dependent Criteria**

Evaluation criteria should be independent. For example, when evaluating humans, Height and Weight are not independent, but Gender (male versus female) and Intelligence Quotient are.

Recommendation: Dependent subcriteria should be grouped together into a single criterion. In selecting a car, the following dependent subcriteria are not independent: Maximum Horse Power, Peak Torque, Top Speed, Time for the Standing Quarter Mile, Engine Size (in liters), Number of Cylinders, Time to Accelerate 0–60 mph. Therefore, they should be grouped into a single criterion, Power.

The nameplate data for an induction motor will usually include rated voltage, peak current, and maximum power. For an induction motor, these may be independent, because peak-starting current is much larger than steady-state current. However, for most other electrical products, voltage, current, and power are dependent.

Before the Transportation Security Administration came into being, a statistician we know refused to fly on airplanes after reading the alarmingly high probability that there could be a bomb on any given plane. Later he found out that the probability of there being two bombs on any given flight was very low. Now, whenever he flies, he always carries a bomb with him!

2.3.3.2 **Relying on Personal Experience**

“We are all prisoners of our own experience.” Criteria may be chosen based solely on the analyst’s experience, with insufficient customer input and environmental confirmation. Uncorrelated to objective knowledge, self-assessed knowledge (what people think they know, as discussed in Section 16) influences their selection of search strategies [49]. Aspects of sole reliance on past personal experience include preconceived notions, false memories, and overconfidence in judgments [50].

Recommendation: It is imperative to engage customers and other stakeholders to acquire balanced and relatively objective views.

Human memory is notoriously fallible. Eyewitness accounts and identification in court trials can be inaccurate and downright harmful [51–53]. Of the criminal defendants who were released on recent DNA evidence, 75 % were convicted based largely on incorrect eyewitness testimony.

Recommendation: Never depend solely on eyewitness testimony; look for corroborating evidence.

2.3.3.3 Forer Effect

Previously existing criteria are likely to be adopted if (1) the analyst believes that the criteria apply to the present problem, (2) the criteria are presented well, and (3) the analyst believes in the *authority* of the previous criteria writer. The analyst might fail to question or rewrite criteria from a legacy trade-off study that originated from a perceived authority and is now seemingly adaptable to the trade-off at hand. This is called the Forer effect [54]. The analyst might fail to question or rewrite criteria from a legacy trade-off study that originated from a perceived authority and is now seemingly adaptable to the trade-off at hand. This is another example of confirmation bias.

Recommendations: Spend time to consider and formulate criteria from scratch, before consulting and automatically reusing criteria in the company Process Assets Library (PAL). Practically speaking, generic criteria taken from a company's PAL must be tailored for the project at hand.

In a famous experiment performed at Yale University by Milgram [55] and replicated by Burger [56], subjects were told to administer electric shocks to a learner when he made mistakes on a list of words he was memorizing. As long as the man in the white coat (the authority) nodded and said, “Go on,” most subjects administered shocks even though they saw that the learner was in excruciating pain.

2.3.4 *Mistakes in Importance Weights*

The sources of mistakes in importance weights are:

- Choice versus calculation
- Ignoring severity amplifiers

Each source of mistakes in importance weights is discussed next.

2.3.4.1 Chosen Versus Computed Value

An importance weight can have different values depending on whether the subject chooses the value from a predetermined set, or calculates a value. For example,

Tversky, Sattath, and Slovic [57, pp. 376–377] told their subjects, “About 600 people are killed each year in Israel in traffic accidents. The ministry of transportation investigates various programs to reduce the number of casualties. Consider the following two programs, described in terms of yearly costs (in millions of dollars) and the number of casualties per year that is expected following the implementation of each program. Which program would you prefer?”

Choose a program		
	Expected casualties	Cost
Program X	500	\$55 M
Program Y	570	\$12 M

Given this “Choose a program” formulation, 67 % of the subjects choose Program X, saying that “human life is priceless.” However, when the same set of alternatives was set up as a calculation problem, where the subjects were asked to calculate a cost for the cell with the question marks that would make Program X and Program Y equally attractive, fewer than 4 % of the subjects chose \$55 M or more as the worth of Program X.

Calculate a value		
	Expected casualties	Cost
Program X	500	???
Program Y	570	\$12 M

In this study, the subjects’ mental values were different depending on whether they chose a value from a predetermined set, or made a calculation.

The importance weight of an evaluation criterion can be determined by choice or by calculation. When a legacy trade-off study is used to guide a current study, the weights are determined by choice. When a trade-off study is constructed from scratch, the weights are calculated for the current alternatives. When faced with a choice involving nonnumerical attributes, people will use principles and categories to make a decision; but when faced with a calculation problem, they will shift a great deal of attention to numbers, ratios and differences, sometimes to the point of making narrow-minded decisions based solely on numbers alone.

Recommendation: The use of choice and calculation should be consistent within a trade-off study. The systems analyst might use one of the formal weight derivation tools referenced in Section 20.

2.3.4.2 Ignoring Severity Amplifiers

When a group of people is asked to assign an importance weight to an evaluation criterion, each individual might produce a different value. Different weights arise not only from different preferences, but also from irrational severity amplifiers [58]. These include the factors of lack of control, lack of choice, lack of

trust, lack of warning, lack of understanding, being human-made, newness, dreadfulness/direness, personalization, memory limitations, and immediacy. Excessive disparities occur when a person assesses an importance weight after framing the problem differently. An evaluation may depend on factors such as how the criterion affects that person, how well that person understands the alternative technologies, and the direness of the results. As a result, each person might assign a different weight of importance to any criterion.

Recommendation: Interpersonal variability can be reduced through education, peer review of the assigned weights, and group discussions. But you need to be aware of the “lemmings-effect.” If you reveal how others are voting, then people are likely to respond with the most popular answers. It is also important to keep a broad view of the whole organization, so that criteria in one area are considered in light of all other areas. A sensitivity analysis can show how important each weight is. For unimportant weights, move on. For important weights, spend more time and money trying to get consensus. This might include showing the recommended alternatives for several different sets of weights.

2.3.5 *Alternative Solution Mistakes*

Mistakes associated with alternative solutions include:

- Serial consideration of alternatives
- Isolated or juxtaposed alternatives
- Conflicting criteria
- Adding alternatives
- Maintaining the status quo
- Uneven level of detail

Each of these categories of mistake is discussed next.

2.3.5.1 **Serial Consideration of Alternatives**

When solving a problem, people often exhibit a confirmation bias [28] by seizing on a hypothesis as a solution, and holding on to it until it is disproved. Once the hypothesis is disproved, they proceed to the next hypothesis and hold on to it until it is disproved [59]. This confirmation bias can potentially persist throughout a trade-off study, as the analyst uses the whole study to try to prove that a currently favored alternative is the best.

Recommendation: Alternative solutions should be evaluated in parallel from the beginning of the trade-off study, so that a collective and impartial consideration permits the selection of the best alternative from a complete solution space.

All alternatives should be given substantial consideration [60]. Strategies that require equal consideration for all alternatives are more effective [61, 62].

2.3.5.2 Isolated or Juxtaposed Alternatives

In the following example the two music dictionaries described in this box were evaluated in isolation and jointly [63].

Music dictionary	Number of entries	Condition
A	10,000	Like new
B	20,000	Cover is torn

When the dictionaries were evaluated in isolation, most subjects were willing to pay more for dictionary A than for B. However, when the dictionaries were evaluated jointly, most subjects were willing to pay more for dictionary B.

The importance weights for the number of entries and the book’s condition evidentially changed. In isolation, each dictionary was judged more critically according to its condition. However, when the dictionary descriptions were juxtaposed, the number of entries became easier to compare, and the importance attached to the number of entries increased. Features that were hard to assess in separate evaluations were easier to evaluate in a comparative setting.

This phenomenon has implications for the selection of alternative solutions. Specifically, solutions that are evaluated serially (perhaps as they are conceived) may not receive the attention they would if they were evaluated in parallel with the other solutions.

Recommendation: New alternative solutions should be stored and be subject to elimination only after comparison to all alternative solutions.

2.3.5.3 Conflicting Criteria

In the following experiment to analyze the effect of conflicting choices, the subjects were told, “You can either select one of these gambles, or you can pay \$1 to add one more gamble to the choice set The added gamble will be selected at random from the list you reviewed” [64].

Conflicting criteria situation			
Gamble	Winning (%)	Payoff	Expected value (not shown to subjects)
X	65	\$15	\$9.75
Y	30	\$35	\$10.40

Result: 55 % of subjects chose to pay for the addition of a yet unknown gamble from a pre-reviewed set

This is an example of conflicting criteria. Gamble X is better on Winning percentage but worse on Payoff and vice versa. Next, the criteria values were changed so that one choice dominated the other and the following result occurred.

Criteria dominance situation			
Gamble	Winning %	Payoff	Expected value (not shown to subjects)
X	65	\$15	\$9.75
Z	65	\$14	\$9.10
Result: 30 % of subjects chose to pay for the addition of a yet unknown gamble from a pre-reviewed set			

In this example, Gamble X is equal to or better than Gamble Z on both Winning percentage and Payoff, so it dominates Gamble Z. It is seen that a choice among alternatives with conflicting features will cause a continued search for alternatives, while the presence of clear dominance among the alternatives will increase the chance of the decider finalizing his or her decision.

Recommendation: Assure that the alternative solutions represent the global solution space. Do not curtail the search for alternatives when you perceive criteria dominance by one alternative.

2.3.5.4 Adding Alternatives

A similar study in medical decision-making [65] investigated distinctiveness by adding alternatives. The objective was to determine whether situations involving multiple options could paradoxically influence people to choose an option that would have been declined if fewer options were available. The following problem statement was given to the subjects:

The following patients have been scheduled for carotid endarterectomy [cleaning of plaque from the carotid arteries that supply the brain with blood], but only one operating room slot is available (more slots will not be available for 2 weeks). Of these patients, who should have a higher priority?

Patient M. S. is a 52-year-old employed journalist with TIA’s (Transient Ischemic Attack: a mini-stroke caused by temporary interruption of blood supply to an area of the brain) experienced as transient aphasia. She has had one such episode occurring 10 days ago which lasted about 12 h. Angiography shows a 70 % stenosis of the left carotid. Past medical history is remarkable (noteworthy) for past alcoholism (no liver cirrhosis) and mild diabetes (diet controlled)

Patient A. R. is a 72-year-old retired police officer with TIA’s experienced as left hand paralysis. He has had two such episodes over the last 3 months with the last occurring 1 month ago. Angiography shows a 90 % stenosis of the right carotid. He has no concurrent medical problems and is in generally good health.

One group of decision makers was given just these two choices: patients M. S. and A. R. and were asked on which patient they should operate first. 38 % chose Patient A. R.

Another group of decision makers was given an additional patient.

Patient P. K. is a 55-year-old employed bartender with TIA's experienced as transient monocular blindness. She has had one such episode a week ago, that lasted less than 6 h. Angiography shows a 75 % stenosis of the ipsilateral carotid. Past medical history is remarkable for ongoing cigarette smoking (since age 15 at a rate of one pack per day).

In the group of decision makers that was given all three patients, 58 % chose Patient A. R. This is counter intuitive, because when you add an alternative you would expect all of the existing alternatives to get fewer votes. Phrased another way, when there were two patients, M. S. got 62 % of the votes and when there were three patients, she only got 33 % of the votes.

Adding an additional alternative can increase decision difficulty and thus the tendency to choose a distinctive alternative. Note that the distinctiveness of the alternative was rather unnoticeable before the additional alternative was added.

Recommendation: All alternative solutions should be evaluated in parallel from the beginning of the trade-off study. If an alternative needs to be added in the middle of a study, then the most similar alternative will lose support.

Here is a different example of adding alternatives. People at a movie theater were offered a choice of a small box of popcorn for \$3 or a large bucket for \$7. Most, 80 % chose the small size. Then another group was offered a choice of a small box of popcorn for \$3, and an *addition* medium sized box for \$6.50 or a large bucket for \$7. This time most chose the large size.

Here is a third example of the effect of adding alternatives. A group of study participants was offered the opportunity to buy a bottle wine. They were offered three merlots from the Napa Valley. They were priced at \$8, \$26, and \$31. Most chose the \$26 bottle. Some said that the \$8 bottle seemed too cheap. Some said that they seldom buy the most expensive item on a list. Then a \$52 bottle of wine was added to the display and it was shown to a new group of people. This time a lot of people bought the \$31 bottle that few had bought before. Marketers know all about this. If they put out such a display, they never expect to sell the \$52 bottle. It is only there to coax more people into buying the \$31 dollar bottle. But capitalizing on such biases is risky business.

2.3.5.5 Maintaining the Status Quo

In another experiment, students were given \$1.50 for filling out a questionnaire [64]. They were then offered either a metal zebra pen for their \$1.50, or they were offered a choice of a metal zebra pen or two plastic pilot pens for their \$1.50. The probability of keeping the \$1.50 was lower when they were offered only the zebra pen (25 %) than when they were offered the choice of pens (53 %). An increase

in the conflict of the choice thus increased a decision to stay with the status quo. It seems that the students thought the increase in conflicts within the subset of pen options increased the chance of making a bad choice within the subset.

Thus to change behavior, do not denigrate an existing concept. Rather extol the virtues of a new concept, because people are more willing to accept a new concept than to reject an old one.

Recommendation: The more alternatives that exist and the more complicated the decision, the more the status quo is going to be favored. Do not needlessly increase the number of alternatives in a trade-off study. Having more alternatives increases the difficulty of the decision. However, in the very beginning of a project it is good to have many alternatives to better understand the problem and requirements.

In another similar scenario involving a patient with osteoarthritis, family physicians were less likely to prescribe a medication (53 %) when deciding between two medications than when deciding about only one medication (72 %). The difficulty in deciding between the two medications led some physicians to recommend neither.

This mental mistake has a very big part in the Monty Hall paradox of Section 16. We did not tell you at that time, but over 90 % of the contestants refused to switch.

2.3.5.6 Uneven Level of Detail

Uneven level of detail in the description of the alternatives is likely to confuse a naive reader. If alternatives are abstracted at a different level of detail, it will be difficult to assign scores to the alternatives.

2.3.6 *Evaluation Data Mistakes*

Evaluation data mistakes fall into the following categories:

- Relying on personal experience
- Magnitude and reliability
- Judging probabilities poorly

Each category is discussed next.

2.3.6.1 Relying on Personal Experience

Estimates for evaluation data may faultily come from personal experiences. People may be completely oblivious to things they have not experienced, or they may think that their limited experience is complete. What people think they know may be different from what they actually know (remember Section 16) [66].

Recommendation: The source of evaluation data for public projects must be subject to peer and public review. Decision analysts must be willing to yield absolute control over choosing evaluation data.

2.3.6.2 Magnitude and Reliability

Numbers have two components: value and variance. People tend to judge the validity of data first on its magnitude or strength (expected value) and then according to its reliability or variance [67]. Therefore, data with outstanding magnitudes but poor reliability are likely to be chosen and used in trade-off study. Remember that when our bumblebees of Table 2.3 were choosing between alternatives that were identical with respect to quantity and quality of reinforcement (expected value), but differed with respect to the probability of reinforcement they preferred the alternative with the lower variance.

Recommendation: Either data with uniform reliability should be used, or the speciousness of data should be taken into account.

2.3.6.3 Judging Probabilities Poorly

Humans are poor at judging probabilities. Now it is worth recalling (Fig. 2.9) that probabilistic evaluation data usually come from guesses by domain experts. Later, these guesses are replaced by quantitative estimates, then with simulations, and finally by prototypes. So, initial data often come from human evaluation and humans are terrible at estimating probabilities, especially for events with probabilities near 0 or 1 [11]. People overestimate events with low probabilities, like being killed by a terrorist and they underestimate high probability events, such as adults ultimately dying of cardiovascular disease. The existence of state lotteries depends upon such overestimation of small probabilities. On the right side of Fig. 2.9, when you are about to depart on an airplane flight, your probability of a safe landing is almost 1.0. But while waiting in the terminal, a lot of people buy flight life insurance.

Recommendation: Distrust human probability estimates, especially for improbable and very probable events. Use frequency of occurrence or likelihood of occurrence instead of probability.

Typically, risk is defined as the probability of occurrence times the severity of consequences. Therefore, half of a risk analysis is based on a task that humans do poorly.

Subjective Probability

In general, people tend to overestimate small probabilities—perhaps gambling on the unlikely, but possibly important appearance of some phenomenon. Please recall

Fig. 2.9. People also tend to underestimate large probabilities—perhaps because a more commonly occurring phenomenon loses psychological impact [11, 68, 69].

Surprisingly, this curve seems to be reversed for children [70], who tend to underweight small probabilities and overweight high probabilities.

Certainty Effect

People prefer reducing chances of something bad happening from something to nothing, more than reducing chances of something bad happening by the same amount but not to zero. Plous [71, p. 99] writes, “Zeckhauser observed that most people would pay more to remove the only bullet from a gun in Russian roulette than they would to remove one of four bullets.” Notice that the reduction in probability of being shot is the same in both cases. (In the first case from 1/6 to 0 and in the second from 4/6 to 3/6.) The certainty effect can be seen to affect scoring functions. Since scoring functions by definition give scores between 0 and 1, they always approach small numbers (or their difference) at their endpoints.

Sub-additivity

This morning, Mr. Smith’s car engine did not start. He had to call a mechanic. Rate the following probabilities for the cause of the malfunctioning.

No gas in the tank	P1
Insufficient battery charge	P2
Faulty carburetion	P3
Other causes	P4

A definite wrong answer is that: $P1 + P2 + P3 + P4 < 1$
However, mechanics with over 15 years of experience are almost invariably prone to considerable sub-additivity effects.

Super-Additivity

An instance of super-additivity occurs when complementary, yet mutually exclusive, probabilities are judged to add up to greater than a 100 % chance of occurring.

P(a): What is the probability that the freezing point of gasoline is lower than the freezing point of alcohol?

P(b): What is the probability that the freezing point of alcohol is lower than the freezing point of gasoline?

- Wrong answer: $P(a) + P(b) > 1$

The ease and the speed with which we can mentally summon seemingly relevant instances are of decisive importance in producing this error.

2.3.6.4 Ignoring the First Measurement

Often when a measurement (test) reveals an unexpected result, the physician and/or the patient will ask for a second measurement. If the second measurement is satisfactory, then the first measurement is discarded and only the result of the last measurement is recorded. This is probably related to confirmation bias. The decision maker rejects the results of all tests until one confirms the decision maker's preconceived notions.

Recommendation: If there is no evidence showing why the first measurement was in error, then it should not be discarded. A reasonable strategy would be to record the average of the two measurements. For example, if you take your blood pressure and the result is abnormally high, then you might measure it again. If the second measurement indicates that blood pressure is near the normal range, and you do not have proof that the first reading was a mistake, then do not record only the second reading, either record both measurements or record the average of the two readings.

2.3.7 Scoring Function Mistakes

Scoring function mistakes fall into three categories:

- Mixing gains and losses
- Not using scoring functions
- Anchoring

2.3.7.1 Mixing Gains and Losses

With scoring functions (such as the utility curve of Fig. 2.8), objective value is translated to subjective utility. Input values become normalized output scores. Scoring functions must be elicited from the customer (Fig. 2.13).

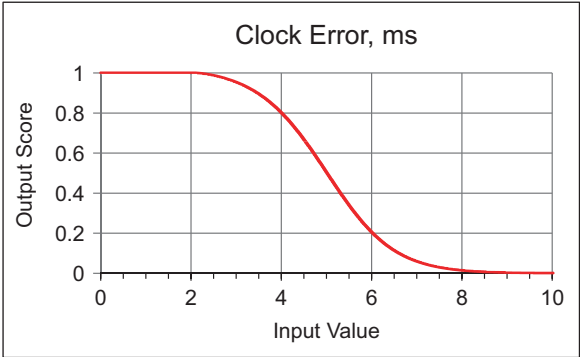
2.3.7.2 Treating Gains and Losses Equally

Loss/Gain Utility Disparity

Loss Aversion

It is important to realize that people do not treat gains and losses equally. Figure 2.8 shows how values are translated into utilities according to prospect theory. People

Fig. 2.13 A scoring function where less is better



prefer to avoid losses more than to acquire gains. Prospect theory [16] suggests that psychologically losses are twice as powerful as gains. Would you rather get a 5 % discount, or avoid a 5 % penalty? Most people would rather avoid the penalty. In a trade-off study, you will get a different result if the scoring function expresses losses rather than gains.

The same change in price, framed differently, has a significant effect on consumer behavior. Though traditional economists consider this to be completely irrational, it is important to the fields of marketing and behavioral economics. The implicit assumption of conventional economics is that the only relevant metric is the magnitude of the absolute change in expenditure. In the above example, *saving* 5 % is considered equivalent to *avoiding* paying 5 % extra.

The **Pinewood Derby Trade-off Study** is a real-world trade-off study that also serves as a reference model. The original study was published in Chapman, Bahill, and Wymore [72, Chapter 5] <http://sysengr.engr.arizona.edu/pinewood.pdf>. It was subsequently implemented in Excel with a complete sensitivity analysis.

Over 80 million people have participated in Cub Scout Pinewood Derbies. Pinewood is a case study of the design of a Cub Scout Pinewood Derby for one particular scout pack. The system helps manage the entire race from initial entry through final results. Many alternatives for race format, scoring, and judging are presented [72, p. 83].

The Pinewood Derby trade-off study had these criteria

- Percent Happy Scouts
- Number of Irate Parents

Because people evaluate losses and gains differently, the preferred alternatives would have been different if they had used

- Percent Unhappy Scouts
- Number of Ecstatic Parents

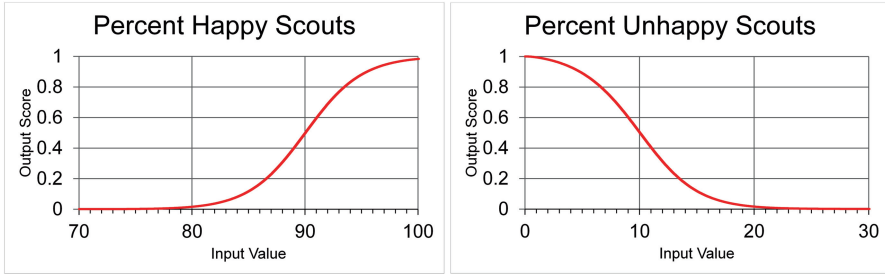


Fig. 2.14 Scoring functions for a Pinewood derby

Recommendation: Scoring functions in a trade-off study should express gains rather than losses. When the Percent Happy Scouts scoring function of Fig. 2.14 (top) is shown to people, and they are asked, “How would you feel about an alternative that gave 90 % happy scouts?” they typically say, “It’s pretty good.” In contrast, when the Percent Unhappy Scouts scoring function of Fig. 2.14 (bottom) is shown to people and they are asked, “How would you feel about an alternative that gave 10 % unhappy scouts?” they typically say, “It’s not very good.” When people are allowed to change the parameters, they typically push the baseline for the Percent Unhappy Scouts of Fig. 2.14 scoring function to the left.

Human unequal treatment of gains and losses suggests that scoring functions in a trade-off study should uniformly express either gains or losses. Principles of linguistic comprehensibility suggest that criteria should always be phrased in a positive manner, for example, use Uptime rather than Downtime, use Mean Time Between Failures rather than Failure Rate, use Probability of Success rather than Probability of Failure, and use Clock Accuracy rather than Clock Error. Therefore, when using scoring functions make sure more output is better, not like Fig. 2.13.

Recommendation: Scoring functions in a trade-off study should uniformly express gains rather than losses.

2.3.7.3 Not Using Scoring Functions

In *infrastructure bias*, the location and availability of preexisting infrastructure such as roads and telecommunication facilities influences future economic and social development. In science, an availability bias is at work when existing scientific work influences future scientific observations. For example, when sampling pollutants, most samples may be taken in towns or near roads, as they are the easiest places to get to. Other examples occur in astronomy and particle physics, where the availability of particular kinds of telescopes or particle accelerators acts as constraints on the types of experiments performed.

Most trade-off studies that we have observed in industry did not use scoring functions. In some cases, scoring functions were explained in the company engineering process, but for the sake of convenience, they were not used.

Recommendation: Standard scoring functions [46] (or similar functions, or fuzzy sets or utility functions) should be used in trade-off studies. Easy to use scoring functions should be referenced in company systems engineering processes.

2.3.7.4 Anchoring

When estimating numerical values, a person's first impression dominates all further thought. In this example from Piattelli-Palmarini [6] that was shown in Section 16, people were shown a wheel of fortune with numbers from one to hundred. The wheel was spun and then the subjects were asked to estimate the number of African nations in the United Nations. If the wheel showed a small number, like 12, the subjects inevitably underestimated the correct number. If the number on the wheel were large, like 92, the subjects overestimated the correct number.

Recommendation: View the problem from different perspectives. Use different starting points. When estimating values for parameters of scoring functions, think about the whole range of expected values for the parameters. For example, when estimating the baseline for the Percent Happy Scouts of Fig. 2.14 (top), the systems engineer could show the expert two scoring functions, one with a baseline of 80 and another with a baseline of 98. Then allow the expert to express his or her preference.

Recommendation: The order in which the alternatives are listed has a big effect on the values that humans assign to the evaluation data. Therefore, a trade-off study matrix should be constructed showing the evaluation criteria in the rows and the alternatives in the columns. Then the trade-off study matrix should be filled out row by row with the status quo as the first alternative. This makes the evaluation data for the status quo the anchors for estimating the evaluation data for other alternatives. This strategy implies that the anchoring alternative is known, is consistent and as importantly you have control over it. Make the status quo the first alternative. In the first iteration, examine the scores left to right, and in the next iteration examine them right to left.

2.3.8 Output Score Mistakes

The key category of output score mistake is:

- False precision

This is discussed next.

The most common mistake in trade-off studies is implying false precision. For example, an analyst might ask a subject matter expert to estimate values for two criteria. The expert might say something like, "The first criterion is about 2 and the

second is around 3.” The analyst inserts these numbers into a calculator and computes the ratio as 0.666666667. This degree of precision is totally unwarranted, but these nine significant digits may be used throughout the trade-off study. The Forer Effect might explain this. The analyst believes that the calculator is an impeccable authority in calculating numbers. Therefore, the calculation is not questioned.

Recommendation: Use significant digit methodology. Furthermore, in numerical tables, print only a sufficient number of digits after the decimal place as is necessary to show a difference between the preferred alternatives and others.

2.3.9 Combining Function Mistakes

Combining function mistakes fall into the following two categories:

- Lack of knowledge
- Lack of availability

Each category is discussed next.

2.3.9.1 Lack of Knowledge

The typical engineer is not familiar with the nuances of combining functions and their impact on trade-off studies. This is a judgment derived from a 20-year search for effective trade-off studies in industry [73].

Recommendation: Training in the use of combining functions is necessary. Discussions of combining functions are found in Section 22 and in [74, 75].

2.3.9.2 Lack of Availability

Decision support software is invariably equipped with limited types of combining functions. For example, one of the best commercial tools has only the Sum and the Product combining functions. Most others have only the Sum.

Recommendation: Spreadsheet-formulated trade-off studies have the greatest potential to achieve variety in combining functions.

2.3.10 *Preferred Alternative Mistakes*

The three categories of preferred alternative mistakes are:

- Overconfidence
- Ignoring the need for expert opinion
- Failure to talk with the customer

Each of these categories is discussed next.

2.3.10.1 **Overconfidence**

Trade-off studies often begin with overconfidence on the part of the analyst. Thereafter, the analyst continues to maintain a state of overconfidence without examining details. Griffin and Tversky [67, p. 411] state,

People are often more confident in their judgments than is warranted by the facts. Overconfidence is not limited to lay judgment or laboratory experiments. The well-publicized observation that more than two-thirds of small businesses fail within 4 years [76] suggests that many entrepreneurs overestimate their probability of success [77].

Recommendation: To compensate for this bias, there is no better teacher than performing trade-off studies and then presenting the results at reviews that demand high-quality work in all trade-off study components.

Consider the following example. A ball and a baseball bat together cost \$110. The bat cost \$100 more than the ball. How much does the ball cost? Kahneman models the human brain as two systems, cleverly named System 1 and System 2. System 1 relies on frugal heuristics yielding intuitive responses. It is quick, but sometimes wrong. It says that the ball cost \$10. System 2 relies on deliberate analytical reasoning. It is slower, but often more accurate. It says that the ball costs \$5. This is the right answer.

2.3.10.2 **Ignoring the Need for Expert Opinion**

The analyst holds a circular belief that expert opinion or review is not necessary because no evidence exists that suggests the need for expert opinion. This is especially true if no expert has ever been asked to comment on the trade-off study.

Humans store about seven units or “chunks” of information at a time [78], in short-term memory, irrespective of skill level. However, chess masters’ chunks are larger and richer in information than amateurs’ chunks [79]. Thus, a novice often “can’t see the forest for the trees,” and cannot perceive the refinement that occurs in an expert’s thought.

Recommendation: Experts should be sought formally or informally to evaluate trade-off studies.

2.3.10.3 Cannibals

Five cannibals manage to get hired as engineers in an aerospace defense company. As part of welcoming them, the boss says, “You’re all part of our team now. You can earn good money here. Our cafeteria is conveniently located for you to run over and get something to eat when you want. So try not to trouble other employees with trivial questions.” The cannibals promised. Four weeks later, the boss returns and says, “You’re all working hard. I’m satisfied with all of you. However, one of our janitors is missing. Would any of you know what happened to him?” The cannibals shake their heads indicating that they did not. After the boss leaves, the leader of the cannibals admonishes the others, “Which of you idiots ate the janitor?” A hand raises hesitantly. The leader scolds, “You fool! For four weeks, we’ve been eating experts and no one noticed anything. And now you had to go and eat a janitor!”

2.3.10.4 Failure to Talk with the Customer

The second most common trade-off study mistake is failing to talk to the customer. Both students and engineers seem to feel that it is a sign of weakness to ask for help.

Recommendation: Talk with your customer.

2.3.11 *Sensitivity Analysis Mistakes*

The categories that go with a mistake in sensitivity analysis are:

- Lack of training
- Hawthorne effect

Each is discussed next.

2.3.11.1 Lack of Training

Most personnel are not well trained in the use of methods and tools for sensitivity analysis. They often fail to find interactions by computing second-order partial derivatives. When estimating partial derivatives they often use too large a step size. When estimating partial derivatives of functions of two parameters, they often use the wrong formula. Smith et al. [80] has showed that interactions among parameters in trade-off studies can be very important, step sizes for the approximation of effects should be very small, and second-order derivatives should be calculated accurately. It is expected that only the highly trained personnel will know of such results, illustrating the gap between reality and training.

Recommendation: Investments in sensitivity analysis training is worthwhile. Perhaps enabling software can substitute for much sensitivity analysis knowledge. Section 26 describes the use of sensitivity analyses.

2.3.11.2 Hawthorne Effect

Individuals may alter their behavior simply because they know they are being studied. In a research project from 1927 to 1932 in the Hawthorne Plant of the Western Electric Company in Cicero, Illinois, workers improved in performance for no other reason than that human attention was given to them. This research was initiated by Mayo [81]. They studied the physical and environmental influences of the workplace (for example, brightness of lights, temperature, and humidity) on human performance and later moved into the psychological aspects (for example, coffee breaks, group pressure, working hours, and managerial leadership) [82].

These studies showed that regardless of the experimental manipulation employed, the productivity of the workers improved because of the attention from the experimenters. Other findings of the study were that (1) the workplace is a social system, (2) the informal organization of work groups and their internal norms for behavior affect performance, and (3) the measured aptitude of individuals is often a poor predictor of their performance.

Studies in the 1960s [83] produced similar behavior changes that the author called the Pygmalion Effect. When teachers were told that a certain group of randomly selected students was expected to perform particularly well in that school year, the teachers' expectations for those students increased. With increased expectations, the students performed better. This effect was repeated in military training centers and in business. According to these studies, when managers had high expectations for their employees, the workers became more productive. When military instructors believed that their trainees had superior skills, the trainees performed better.

There is a similar effect in physics, the Heisenberg Uncertainty Principle [84], which describes how precisely we can simultaneously measure the position and momentum of a particle. If we increase the precision in measuring one quantity, we are forced to lose precision in measuring the other.

In other words, interacting with a person or a system will change its behavior. Giving added attention to workers will increase their productivity. Having higher expectations for students will increase their performance. Increasing the precision in measuring position or momentum of a small particle will decrease the precision in measuring the other. You will be studying alternatives and you will be measuring system performance using evaluation criteria. Be sure that you understand how your activities affect the behavior of the system. You will be interacting with decision makers. They will change their minds. Understand how your interactions affect them. Your decision makers will change their preferences; however they should not change their values. They also should change their propensity for making mental mistakes.

Your job is to help a decision maker to make valid and effective decisions that he or she (and other stakeholders) can have confidence in. This is a difficult and iterative task. It entails discovering the decision makers preferred weights, scoring functions, and combining functions. You must also discover the decision maker's mental mistakes and ameliorate them or mitigate their impact. You must get into the head of the decision maker to discover his or her values.

It is important to recognize that different people have different personality types. The Myers-Briggs model [85] is one way of describing personality types. In the language of this model, Sensing-Thinking, Thinking-Judging people are likely to appreciate the trade-off study techniques we will present. Intuitive-Feeling-Perceiving people most likely will not.

2.3.12 Section Summary

Humans usually consider alternatives sequentially. They often hastily choose one alternative after having their attention anchored to just one or a few criteria. To make good, rational choices among alternatives, a decision maker's awareness of cognitive biases must increase. Limited awareness and possible consequential irrationality can cause erroneous estimation or misuse of trade-off study components. Therefore, trade-off study components should be examined individually. The higher level decision then becomes a calculation resting on a broad base of rationally considered assumptions, components, and calculation methods. Decision makers should understand the mathematical methods that allow the parallelization of human decision processes through trade-off studies.

2.3.13 Homework

2.3.13.1 Accelerated Life-Cycle Testing

On one episode of the TV series MythBusters, they investigated myths concerning pirates. In particular, they wanted to know if pirates could have removed stains from blood, sweat, and tears from their clothing with urine. The pirates were said to have one barrel that all the pirates urinated in. After a few months, they would use that stale urine to wash their clothes and take stains out. The MythBusters did not want to wait a few months for the urine to get stale, so they boiled it down to 50 % of its volume. What mental mistake does this illustrate.

2.3.13.2 Mental Mistakes in the Spin Coach

The following is from the Spin Coach documents. Point out mental mistakes that you find.

Document 1: The Problem Situation

When a spinning object (like a baseball) is put in a moving fluid (like air) it will experience a force that pushes it sideways. Some highly successful baseball players have written that they see this spin of the ball and use this information to predict its future trajectory. But at present, there is no system that can teach high school and college baseball and softball players to predict this spin-induced deflection of the pitch. Our customer needs such a system. The goal of this project is to design a web site that will display images of spinning baseballs, allowing the subject to predict the spin induced deflection and providing feedback to facilitate learning.

Document 5: Concept Exploration

Alternative architectures for the Spin Coach

3. System on CD-ROM. Balls spinning on drills can be photographed and their images stored on CD-ROM disks. Such videos are on my web site. <http://www.sie.arizona.edu/sysengr/baseball/index.html> under the tag line “here is a ten-second video of the four-seam (left) and two-seam (right) fastballs. These images along with the software program (application) will be transferred from the CD-ROM to the user’s hard disk using a license key provided by BICS. Thereafter the user runs the Spin Coach from his or her hard disk. The user must login for each session. The information gathered at login is used to track user performance history. System upgrades will be provided with new CD-ROMs.
- 3b. Application Sold Online. A slight variant of the CD-ROM alternative is to sell the application through an online store with distribution via Internet downloads.

Evaluation Criteria

Fidelity of Images. How realistic are the images? Are they two or three dimensional? What is the resolution? What is the color depth? What is the update rate? Will the presentation vary depending on the processor speed or the communications bandwidth? This traces to the Operational Concept Description (OCD) and is also related to Validation. Importance weight is 6.

Varying image size. When the pitcher releases a baseball, the ball is 54 ft from the batter’s eye and it subtends 0.26° of arc. When it is two-thirds of the way to the

contact point, when the swing must begin, the ball subtends 0.77° of arc. Perhaps our displays should have a changing image size. This traces to the Operational Concept Description (OCD) and is also related to validation. Importance weight is 4.

Distortion. Are the images distorted? Is the image of the ball circular? Are the images in focus? This traces to the Operational Concept Description (OCD) and is also related to Validation. Importance weight is 7.

Ease of Verification. Verification means proving that our system works correctly. We could help verification by asking, “Can we gather data that shows the player’s progress while using the Spin Coach?” Importance weight is 9.

Ease of Validation. Validity indicates the fidelity of transferring learned knowledge from our product to the real world. We can help validation by asking, “Can we gather data that shows improvements in the player’s performance in the real game?” Importance weight is 9.

Autonomy. Do we control the needed assets, or must we depend on outside sources? Negotiating a contract could take months. Finding and buying equipment might take months. This traces to SR1. Importance weight is 10.

2.3.13.3 What Mistake Was Made Here?

A Modification of SIERRA

	Input/output figure of merit	Weight	Normalized weight
1	Number of collisions	8	0.258065
2	Trips on circular track	7	0.225806
3	Trips on elliptical track	7	0.225806
4	Spurious stops on circular track	3	0.096774
5	Spurious stops on elliptical track	3	0.096774
6	Availability	2	0.064516
7	Reliability	1	0.032258

2.3.14 Summary of Section 18

This section, which is based on an article by John G. Cramer, <http://www.npl.washington.edu/AV/altvw146.html> provides a good summary for this section. Human beings have evolved with brains that have amazing capabilities for rational thought, pattern recognition, judgment, creativity, and imagination, none of which can be readily duplicated by the most powerful computers. However, there is one area in which the human brain is sadly lacking: the ability to accurately assess probabilities and act on these assessments. The successes of state lotteries and

casinos in Las Vegas and on Indian reservations provide ample evidence that when it comes to estimating probabilities and acting accordingly, humans are deficient. Humans erroneously believe that winning streaks are real, that slot machines are overdue to pay off jackpots, and that past patterns of random events somehow influence the odds of occurrence of the next event. Consider the irony in this next story. Long ago, when humans began to emerge from the woods and started to think as humans, there was a wide river separating two hostile tribes that constituted most of humanity. On one side of the river lived the Probabilist Tribe, a group that had the ability to understand probabilities and act accordingly. On the other side of the river lived the Numbskull Tribe, a group more like modern humans who believed in luck and winning streaks, and other such fantasies. The Probabilists and the Numbskulls hated each other and wanted to get rid of each other. On one fateful night, the Probabilists wanted to rush across the river and kill the Numbskulls. So, they did a risk analysis, computing probabilities and consequences. They concluded that it was too risky to cross the river and engage in combat with the Numbskulls. The Numbskulls made no such calculation and felt no such reluctance. On a night when the moon was no more than a crescent, they quietly made their way across the river, and launched a surprise attack on the Probabilists killing them all. Therefore, today we are all descendants of the Numbskulls tribe.

2.4 Section 19. Heuristics: Cost-Effective Shortcuts to Desired Outcomes

Heuristics are mental shortcuts that humans employ when making rapid decision and judgments without spending a lot of time investigating, analyzing, and evaluating problem situations. Heuristics are quick, informal, and intuitive algorithms the brain uses to generate approximate answers to questions that require reasoning. Heuristics have been effective in system architecting, systems engineering, management, and systems integration. Heuristics have been the cornerstone of methods to cope with complexity in systems. The term “heuristics” is short for heuristic reasoning [86, 87]. Heuristics range from declarations (i.e., warnings, cautions) and true statements (i.e., descriptive text without obvious implications) to prescriptions (i.e., effective responses in particular situation)

Effective heuristics tend to exploit contextual and domain knowledge, analogies and analogs, and exemplars and archetypes. Unlike scientific laws, they tend to be qualitative, suggestive, and less amenable to replicable measurements. They tend to be “generalization from specific examples, not conclusions reached from the application of general principles.” The power of a heuristic stems from coverage (breadth) with minimal exceptions (conditions). Heuristics embrace the principle of satisficing instead of optimizing as a means to conquer complexity. Consequently, heuristics do not guarantee a solution, much less an optimal one. Therefore, it is prudent to question heuristics and periodically revisit them in light of evidence. It is entirely possible that a heuristic in use may be discarded in favor of another, based on evidence.

It is important to recognize that heuristics can lead to errors in judgment. When heuristics fail to produce correct judgments, they can result in cognitive biases, i.e., tendencies to draw incorrect conclusions in specific circumstances based on cognitive factors. This is an important concern in that judgements are routinely made in trade-off studies and risk analyses. Khalil Walker states that the difference between a heuristic and a bias is normative judgment. Heuristics are helpful biases, whereas biases are hurtful heuristics. In this regard, there are three heuristics that can have a negative impact on decision-making in general and trade-off studies in particular:

Availability Heuristic: This is a mental shortcut that helps us make a decision based on how easy it is to bring something to mind. In other words, humans tend to think of examples when making a decision or judgement. For example, if one were to ask what percentage of crime involved violence in 2001, most would guess high because of the nonstop news coverage of 9/11 yet the Federal Bureau of Investigation (FBI) reported that violent crimes were less than 12 % of all crimes in the USA in 2001. The main problem with the availability heuristic is that humans tend to assume that if there are several readily available examples, then the event or topic is commonplace. This is not the case in many circumstances.

Representativeness Heuristics: This is a mental shortcut that helps us make a decision by comparing available information to our mental stereotypes. For example, motor cyclists are troublemakers, skateboarders are slackers, and politicians are corrupt. And, of course, we all know how wrong stereotypes can be!

Base Rate Heuristic: This is mental shortcut that helps us make decisions based on probabilities associated with prevailing context. For example, in an unsafe neighborhood, an automobile back firing might be concluded as a gut shot.

In psychology, heuristics are simple, efficient rules, learned or hard-coded by evolutionary processes that have been proposed to explain how people make decisions, arrive at judgements, and solve problems when facing complex problems or incomplete information [88, 89].

Heuristics can vary in power or potency. Table 2.5 presents the characteristics of a powerful heuristic.

Heuristics have been used successfully in architecting, engineering, design, maintenance, and test [86, 87]. Heuristics are the basis for shortcuts, sanity checks, guidance and hints, alternatives processing, and lessons learned. Heuristics cannot be tested in the traditional sense because they are nonquantitative. Therefore, they need to be applied in particular contexts and their efficacy evaluated statistically. Ideally, heuristics should have prescriptive power. Some heuristics written as declarative statements can be rephrased in prescriptive terms.

Table 2.5 Characteristics of a powerful heuristic

• The opposite of a heuristic does not make sense or leads to failure [86]
• Coverage regime with no/few exceptions
• Prescriptive, implies/suggests appropriate action
• Actionable, can be implemented in context

Table 2.6 Defining heuristics (adapted from [92])

• Heuristics do not guarantee a solution
• Two heuristics may contradict/give different answers to the same question and still be useful
• Heuristics permit the solving of unsolvable problems and reducing search time to a satisficing solution
• A heuristic depends on the immediate context instead of absolute truth as a validity standard

For example, consider the popular refrain: “Keep It Simple, Silly (KISS).”
This heuristic can be rewritten as a prescriptive heuristic:

The simplest solution is usually the correct one (Occam’s razor) [90].

Similarly, consider the cautionary (descriptive) heuristic:

Don’t assume that the original problem statement is necessarily the best, or even right

This heuristic can be rewritten in prescriptive form as:

Probe the original problem statement in terms of objectives, assumptions and constraints;
doing so, may result in reformulation/revision of the original problem statement

Heuristics have become an essential aspect of modeling [91]. Heuristics are easy to define using the characteristics offered by Koen [92] (Table 2.6).

A heuristic is anything that provides a plausible aid or direction in the solution of a problem but, in the final analysis, does not guarantee a solution. Its real value is in its ability to guide, discern, and reveal [89, 93].

Heuristics are a key part of Koen’s definition of the engineering method [92]:

The engineering method is the use of heuristics to cause the best change in a poorly understood situation within the available resources

Typical engineering heuristics include:

- Rules of thumb and orders of magnitude
- Safety factors
- Heuristics that determine the engineer’s attitude toward his or her work
- Heuristics that engineers employ to keep risk within acceptable bounds
- Rules of thumbs that are the key to resource allocation

Heuristics that pertain to human decision-making and trade-off analysis [86, 94] are

- It is easier to match the system to the human rather than the other way round
- The probability of implementing new ideas depends on the number of people in the chain leading to their implementation and on the probability that each person understands and retransmits that idea
- If social cooperation is required, the way in which a system is implemented and introduced must be an integral part of its architecture
- The choice between architectures may well depend upon which set of drawbacks the client can handle best
- Build in and maintain options as long as possible in the design and implementation of complex systems. You will need them

- Sometimes, but not always, the way to solve a difficult problem is to expand it

More recently, with the emphasis on adaptive systems, newer heuristics have become important:

- Systems need to be architected for change and extension beyond currently recognized needs
- It is likely that there will be more stakeholders and more needs per stakeholder at the end rather than at the start
- Not all stakeholders can be satisfied equally; thus, trade-off analysis is needed to engage in reasoned compromise to achieve a balance among competing objectives/quality attributes
- Align incentives with desired outcomes to ensure quality and performance don't suffer
- Introduce flexibility in architecture, design, and program to cope with uncertainty and risk.

In the light of the foregoing, Madni [93, 95] compiled a set of prescriptive and actionable heuristics pertaining to decision-making and trade-off analysis for systems architecting and engineering (Table 2.7). These heuristics are classified as modeling, problem solving, system development, and stakeholder management.

Each heuristic in the four categories of Table 2.7 are discussed in the following paragraphs.

1. A model should be only as complicated as needed to answer questions specific to a particular engineering phase in the system life cycle. It is important to realize that no model is complete. The question is whether or not the model development is useful in answering the questions at hand. If the answer is "yes," then the model is deemed useful. What if the model can answer some of the questions but not all? In this case, the model can be refined, elaborated, and disaggregated along dimensions that help answer the remaining questions.
2. Scale up techniques to address the problem; resist at all cost the tendency to dumb down the problem to fit known techniques. Continuing to simplify a problem until it begins to look familiar or resemble something previously known is a common habit that people inadvertently fall into or consciously make to make the problem amenable to being solved using known techniques. This tendency toward oversimplification invariably results in solving a different wrong problem, than the one originally intended. Instead, the problem solver needs to explore other disciplines (e.g., biology, sociology, economics) and new metaphors and paradigms that can help frame the problem in a new light and thereby pave the way for solving the problem of the right scope and at the right scale and complexity.
3. A model needs to be interpreted within the context of use, and not taken as an absolute. All models make assumptions in the absence of required information, or as a means to reduce complexity. When needed information becomes available, the assumptions need to be revisited and revised, and the model

Table 2.7 Prescriptive heuristics [95, 96]

<i>Modeling</i>
1 A model should be only as complicated as needed to answer questions associated with a particular engineering phase or stage in the system life cycle
2 A model needs to be interpreted within its context, and not taken as an absolute
3 It is best not to employ a model for a purpose other than originally intended unless prior provision is made to repurpose the model. Even then, repurposing a model will require adding details (to abstractions), new perspectives, and new visualizations formats
4 Understand models to be an aid, not a replacement for common sense; act accordingly. Model to increase understanding; analyze to increase insight
<i>Problem solving</i>
1 Scale up techniques to address the problem; resist dumbing down problems to fit known techniques
2 Exploit query reformulation (about a problem) to elicit a more complete set of requirements
3 Probe for high level objectives; don't confuse objectives with options
4 Keep the option space open as late as possible to assure ability to select the best option
5 Cross-check results from heuristics with actual testing against high fidelity models
6 Exploit apt analogies from other disciplines such as biology to increase understanding and develop effective solutions, e.g., an ant colony or the human immune system
7 Ensure that the trade space spans the problem domain before undertaking trade space analysis
8 Periodically revisit assumptions and constraints in light of new evidence/data; revise as needed
9 Supplement heuristics with "patterns" and "cases" as appropriate
<i>System development</i>
1 Build in flexibility in the product and process at specific points based on cost-benefit and risk-benefit analysis to ensure the ability to adapt to new circumstances and exploit new opportunities
2 Architect systems to accommodate change and support future extensions that go beyond the current needs of the stakeholders
3 Separation of concerns is a way to manage complexity; it is about striking an effective balance between parts of a system problem/solution while keeping the whole in mind
<i>Stakeholder management</i>
1 (Re)balance people and process perspectives with increasing system complexity
2 Perform process decomposition to a level where the tasks are directly assignable to people, or where automation handles all lower levels
3 Exploit storytelling especially in upfront engineering to ensure participation of all stakeholders
4 Iterate with stakeholders during the requirements engineering phase, because the first pass will not yield a complete set of stakeholders or their needs
5 Incentives and inhibitors shape behaviors; reward value delivered, not milestones met
6 Focus on the decision-making behavior of stakeholders, not just their roles and skillsets
7 Aid human decision-making by recognizing that individuals will often make decisions that satisfice, rather than optimize. This results, in part, because humans lack the necessary bandwidth to assimilate all relevant information and weigh alternatives
8 Groups tend to make bolder decisions than individuals acting alone, but group norms and pressures produce conformity in decision-making in crucial situations

modified accordingly in light of the new context defined by the new assumptions and models.

4. It is best not to employ a model for a purpose other than what was originally intended. However, under special circumstances, if there is a compelling need to do so, then it should be recognized that the model might require elaboration, abstraction, aggregation, or disaggregation before being put to use. There are two examples that stand out in this regard. First, the attempt to use a training simulator network SIMNET [97] as an engineering tool. It was quickly discovered that the approximate models (based on the principle of selective fidelity) that were used for training were inadequate for engineering and had to be redone in terms of computational accuracy. Second, the attempt to use MYCIN (an expert system for medical diagnosis) as a medical teaching system [98]. It was quickly discovered that the models used in MYCIN (an aiding expert system) were not sufficiently detailed for training purposes.
5. Employ problem-related query reformulation to elicit a more complete set of requirements. It has been widely observed that query reformulation about a problem statement can illuminate new perspectives which, in turn, can facilitate the identification of a more complete set of requirements. Restating the problem can also enhance stakeholder participation, because stakeholders may relate to the reformulated problem statement more than the original problem statement.
6. Probe for higher level objectives to ensure that lower level objectives or options have not been inadvertently accepted as objectives. It is important to realize that people often confuse options with objectives. Probing for higher level objectives will avoid this problem.
7. Keep the option space open as late as possible to assure selection of the best possible option when additional information is available. To achieve this objective requires building in sufficient flexibility and not prematurely pruning options before needed information becomes available and uncertainty is reduced.
8. Build in flexibility in the product and process at appropriate points to combat the uncertainty that might exist at that point. This capability is essential to adapt to new circumstances and exploit new opportunities. Real options are an engineering analog of financial options. They provide the ability to introduce flexibility in a cost-effective fashion. Financial options offer the right but not the obligation to exercise an option at a particular price by a particular date. Real options provide targeted flexibility to systems architects and engineers to exploit an emergent opportunity, or cope with change in the face of uncertainty.
9. Models are an aid, not a replacement for common sense; so, act accordingly. It is important to remember that models can be fallible. When they produce results that “fly in the face” of common sense, they should be examined closely. Two possibilities exist here. Either the models are simply wrong, or some unexpected, counter-intuitive phenomenon or behavior has been discovered. Therefore, it is important to ascertain which of the two options hold, and act accordingly.

10. Cross-check results from heuristics with actual testing against high fidelity models and real-world operational tests data. While heuristics provide a cost-effective, shortcut in general, they are fallible. In other words, they don't guarantee a solution, much less an optimal one. Therefore, they need to be validated against higher fidelity, models, and/or real-world testing.
11. Model with the intent of increasing understanding, and analyze (the model) with the intent of increasing insights. The very act of modeling systems increases understanding of the system structure, components, and their relationships. The analysis of the model from different perspectives and over time illuminates system behavior and uncovers dynamic interactions between the system and the environment.
12. Exploit apt analogies from biology, economics, sociology, and other disciplines to increase understanding of the system and develop effective solutions. The ant colony, human immune system, swarming behavior, and real options are all being exploited in multi-UAV missions, cybersecurity, social sciences, and design flexibility. Several analogies of this ilk can be exploited to not only enhance understanding but also discover effective solutions.
13. Ensure that the trade space is sufficiently representative of the problem domain before undertaking trade space analysis. For trade-off analyses to be of value, the trade space should span the problem domain. Various methods exist to expand the trade space, including constraint relaxation, query reformulation, role-playing, question answering, and objective probing.
14. Periodically revisit assumptions, constraints, and beliefs in light of new evidence/data. This practice will allow revision of beliefs and models, and development of new insights. With complex systems, this is even more important.
15. You need to balance people and process emphasis with increasing system complexity. With increasing system complexity, a process description needs to be replaced by human judgment and trade-off analyses. This finding is becoming increasingly more apparent in software development where process-driven development is being replaced by people-driven, process-enabled development.
16. Perform process decomposition to a level where tasks are directly assignable to people or automation. This heuristic is the key to designing systems with different levels of automation. The "done" condition occurs when the tasks at the leaf nodes are directly performed by humans or handed off to automation.
17. Supplement heuristics with "patterns" and "cases" as appropriate to simplify complex problem solving. Patterns enable the transformation of problem-solving activities into pattern-matching activities. Similarly, cases simplify reasoning by providing historical precedents to draw on. The combination of patterns and cases can dramatically enhance systems architecting and engineering when used in conjunction with heuristics.
18. Exploit storytelling to ensure participation of all stakeholders especially in upfront requirements engineering. Storytelling is also compelling in terms of its persuasive powers. In particular, interactive storytelling (for example, in virtual

worlds) can provide insights to all stakeholders by allowing them to explore alternate futures with different assumptions, constraints, and technologies.

19. Architect systems to accommodate anticipated change and support potential extensions that go beyond current stakeholder needs. This is especially necessary for DOD systems that are typically long-lived. Part of this requirement is addressed by Pre-planned Product Improvement (P3I), but part of it needs to be handled “on the fly” when the system encounters unexpected operational environments.
20. Iterate with stakeholders during requirements engineering phase because it is highly unlikely that a complete set of stakeholders or their needs will be identified on the first pass. Therefore, it will invariably be the case that system developers will have to iterate with the stakeholders a few times as needed to define a stable set of requirements. Complicating matters is the fact that systems engineers employ engineering notation to capture system models. This practice leaves out several stakeholders (mostly nonengineers) unfamiliar with engineering notation. To overcome this deficiency several new approaches rooted in interactive technical storytelling in virtual worlds can be employed.
21. Since incentives and inhibitors shape behaviors, reward value delivered, not milestones met. The behavior of developers and program managers, in large part, is shaped by the incentives employed. Tying the reward structure to milestones met or tasks completed says little about the quality of the product being developed. Instead, the reward structure should be tied to the value delivered through the product or service. This strategy ensures that the project team is not being rewarded for going through the motions of satisfying milestones without regard to the quality of the product/service being created.
22. Separation of concerns is a way to manage complexity; it is about striking an effective balance between attending to parts of a system (problem/solution) while keeping the whole in mind. This is a form of the well-known “divide and conquer” strategy in which by looking at the system from separate viewpoints (concerns) allows the stakeholders to get their arms around a complex system. Addressing each concern individually enhances comprehension, communication, and issue resolution.
23. Focus on the decision-making behavior of developers in addition to their roles and skillsets. Traditionally, the focus has been on the roles and skillsets of the development team members. This focus is necessary, but not sufficient. Focus should also be on the information seeking and decision-making behavior of the development team members.
24. Aid human decision-making by recognizing that individuals will often make decisions that satisfice, rather than optimize. This behavior results in part from the lack of cognitive bandwidth to assimilate all relevant information and weigh alternatives. Humans can conduct limited search and are poor at aggregating information. This circumstance calls for decision aiding/automation to overcome human cognitive limitations.
25. Resist “group think” but employ teams whenever possible to address different aspects of a problem. Groups tend to make bolder decisions than individuals

acting alone, but group norms and pressures produce conformity in decision-making in crucial situations. Thus, it is also important to encourage divergent thinking.

2.4.1 Homework for Section 19

2.4.1.1 Powerful Heuristics

Table 2.5 states that for a powerful heuristic the opposite of the heuristic does not make sense or leads to failure. The following are some heuristic from Rechlin and Maier [86, 87]. Rewrite them so that they say the opposite. Do they make sense? Which do you follow?

“In architecting a new software program, all the serious mistakes are made in the first day.”

“The most dangerous assumptions are the unstated ones.”

“Do the hard parts first.”

“If you can’t explain it in five minutes, either you don’t understand it or it doesn’t work.”

In a medical “triage: let the dying die. Ignore those who will recover on their own. And treat only those who would die without help.”

It is easier to match the support system to the human it supports than the reverse. The number of defects remaining in a software system after a given level of test or review is proportional to the number found during that test or review.

“High quality, reliable systems are produced by high quality architecture, engineering, design and manufacture, not by inspection, test and rework.”

“Before ordering a test decide what you will do if it is (1) positive or if (2) it is negative. If both answers are the same, then don’t do the test.”

2.4.1.2 How Do Heuristics Help

Give an example of how heuristics can allow one to attack a complex problem successfully.

Dumb Things

What kinds of biases can cause competent people to do “dumb” things?

2.4.1.3 Trade Space Exploration

How do heuristics help with trade space exploration?

2.4.1.4 Domain-Specific Heuristic

Give an example of a domain-specific heuristic and explain how it helps with problem solving.

2.4.1.5 Upsides and Downsides

What are the upsides and downsides of using heuristics?

2.4.1.6 Expert Knowledge

In what ways can heuristics codify expert knowledge?

2.5 Summary

This chapter covered common mental mistakes that people make. Mistakes that can adversely affect trade-off studies and risk analysis. We began by providing instances of erroneous knowledge that people carry in their heads. We then reviewed prospect theory, a Nobel Laureate's collection of erroneous human thinking. A dozen examples of mental mistakes that people tend to make when conducting trade-off studies and risk analysis were presented. We then addressed heuristics and cognitive biases that come into play when conducting trade-off studies.

Imagine that you find yourself in a position to help a decision maker make informed trade-offs and defensible decisions. We know that when viewed in formal terms these are difficult, iterative tasks. They entail discovering the decision maker's importance weights, scoring functions, and preferred combining functions. To accomplish this discovery, you need to get into the head of the decision maker to discover his or her preferences and values. As importantly, different people have different personality types. The Myers-Briggs model is one way of describing these personality types. *Sensory-Thinking-Judging* people are likely to appreciate the decision-making concepts that we have presented. *Intuitive-Feeling* people might not appreciate them. Nonetheless, having an understanding of the foregoing concepts can potentially help you in understanding the values and preferences of the decision maker.

In Section 16, we discussed human foibles that can adversely impact trade-off analysis. Specifically, we discussed the salient differences between rational and irrational human behavior. We defined a rational decision as one that requires a goal, perfect information, and an optimal course of action that maximizes the expected value of the decision. We noted that this is the *prescriptive* model of decision-making. In particular, we defined an optimal course of action as one that, in the long run, is more valuable (or profitable) than any other available course of action. We then provided several examples of rational decision-making. Thereafter, we discussed how people actually make decisions, the *descriptive* model. We introduced the concept of *satisficing* attributed to Nobel Laureate, Herb Simon. We then gave several examples of humans not being rational decision makers, and making decisions and reaching conclusions not supported by facts. We discussed cognitive illusions and how they can impair judgment and adversely impact decision-making. In keeping with our overall philosophy of the structure of each section, we provided homework problems to reinforce the concepts in Section 16. In Parts V and VI, we will show how trade-off studies and risk analyses can help move an individual toward making decisions that are more rational.

In Section 17, we covered prospect theory developed by Tversky and Kahneman. We noted that this theory explained the subjective nature of decision-making in terms of heuristics and biases that are ever-present in human assessment of information, and the commonly observed deviations from rational decision-making that results as a consequence. We defined key terms such as Expected Value Model of human decision-making, and clarified the distinction between Value and Utility, and between Objective Probability and Subjective Probability. We presented Edward's four-quadrant representation of the four variations on the Expected Value Model. We then applied prospect theory to the Expected Value model to realize a descriptive model of human decision-making.

After reviewing the theoretical foundations of decision-making and human fallibility in estimating probabilities, we drew specific implications. We cautioned the reader about the existence of cognitive biases even in extensively vetted analysis, a contention of prospect theory. We discussed how biases and illusions can influence trade-off studies and risk analysis, and cause them to produce irrational decisions.

We then focused on *risk* and noted that systems engineers and decision theorists use the word differently. To avoid confusion, we chose to focus on terms such as ambiguity, uncertainty, and hazards that have common interpretations in both the systems engineering and decision sciences communities. We discussed the existence of human filters that are responsible for biases. We noted that confirmation bias is the most prevalent and important in that humans hear what they want to hear and tune out the rest. Said differently, humans filter information that contradicts their preconceived notions (biases), and remember things that reinforce their beliefs.

We discussed the concept of *severity amplifiers* and gave specific examples, including lack of control, lack of choice, lack of trust, ambiguity, uncertainty, and immediacy. We concluded this section by stressing the significance of the Myer-

Briggs model as an effective instrument to describe personality types and explain how personality types influence decision-making. In addition to human foibles described by prospect theory, we noted that there are several other factors that affect human decisions. These include corporate culture, information displayed, wording of questions, context, the decision itself, the effort required to make the decision, the difficulty in making the decision, the time available to make the decision, needed decision accuracy, cost of the decision, likelihood of regret and, finally, the decision maker's values, personality types, risk averseness, biases, illusions, and use of heuristics.

In Section 18, we covered potential mental mistakes made in trade-off studies. We cautioned that humans are susceptible to mental mistakes, and identified several mental mistakes that people make when conducting trade-off analyses. We reviewed prospect theory, which breaks down subjective decision-making into a preliminary screening stage and a secondary evaluation stage. We defined the seven key components of a trade-off study and identified issues in each component that can potentially compromise the results of a trade-off study. We illuminated some of the key points using the Pinewood Derby Trade-off Study as a real-world example.

We noted that humans tend to consider alternatives sequentially during decision-making. They often hastily choose one alternative after having their attention anchored in just one or a few criteria. We cautioned that to make good, rational choices among alternatives, a decision maker needs to become aware of cognitive biases. Limited awareness and possible consequential irrationality can cause erroneous estimation or misuse of trade-off study components. Therefore, trade-off study components need to be examined individually. The higher level decision then becomes a calculation that rests on a broad base of rationally considered assumptions, components, and calculation methods. We recommended that decision makers should understand the mathematical methods that allow the parallelization of human decision processes through trade-off studies. We followed up with a set of homework problems that reinforced the key points made in Section 18.

In Section 19, we discussed the body of knowledge associated with heuristics and explained how heuristics can potentially provide effective shortcuts to complex problems. In particular, we identified three heuristics that could negatively impact trade-off studies: the availability heuristic, the representativeness heuristic, and the base rate heuristic. We defined the characteristics of a powerful heuristic and showed how a descriptive heuristic can be transformed into a prescriptive heuristic that is actionable. We provided examples of this transformation. We followed that up with specific criteria for defining heuristics, typical engineering heuristics and heuristics that pertain to human decision-making and trade-off analyses. We then focused on heuristics that specifically pertain to adaptive systems. Thereafter, we presented Madni's prescriptive heuristics that span modeling, problem solving, system development, and stakeholder management. Finally, we described each heuristic under these four categories in greater detail, and followed up the discussion with homework problems to reinforce these concepts.

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