The English-language thesaurus has the following synonyms for “fuzzy”: ill-defined, indefinite, indistinct, murky, obscure, unclear, vague, and so on. These are words that English-speaking people associate with fuzzy logic, fuzzy control, fuzzy identification, and fuzzy systems. They are not words that anyone would want associated with engineering systems, on which may depend large sums of money, or even worse, peoples’ lives. It is unfortunate that the word “fuzzy” was chosen to describe the type of identification and control described in this book. Japanese has no such negative connotations associated with the word “fuzzy,” hence systems utilizing fuzzy identification and control are far more prevalent in Japan than in English-speaking countries.

Fuzzy logic, as will be seen in Chapter 3, is modeled on the human reasoning process. Therefore, fuzzy logic is about as “fuzzy” as humans are. A well-designed system utilizing fuzzy logic to perform a task is roughly as dependable at performing the task as a human competent at performing the task would be. Two fuzzy systems designed by different designers to perform the same task may perform it slightly differently, depending on several choices made in the designs. This difference is analogous to the difference that would exist when two different people perform the task, or even the same person on different days. For example, two pilots will land an airplane slightly differently, but each can land it unfailingly every time.

1.1 FUZZY SYSTEMS

When you are driving and choosing which route to take to a desired destination, you usually have several candidate routes from which to choose. You have a set of rules (probably unspoken) in your mind that help you decide which route to take. They might be something like, “If the route distance is short and it does not have many turns, and it does not go on crowded streets, then the route is desirable.” Another might be, “If the route goes on narrow streets and it goes close to the area that I just heard on the radio is congested, and it is rush hour, then the route is undesirable.” You might have several rules like these in your head, and for any given situation you must somehow balance them all to arrive at the route you will take. This
decision process is a fuzzy system, and people employ this kind of reasoning all the
time, from deciding how to invest their money to deciding which restaurant to
go to.

Fuzzy systems are capable of dealing with very complex problems—problems
that would be impossible to model mathematically—such as deciding when, where,
and how much money to invest. Furthermore, fuzzy systems are employed with
success by people with absolutely no technical expertise whatsoever. For instance,
a young boy can easily balance an upside-down broom in the palm of his hand for
any desired length of time (I remember doing this myself when I was 11). In engi-
neering parlance, this is known as the two-dimensional inverted pendulum problem.
This system is difficult to model mathematically, and it is not straightforward to
design a controller to keep the broom balanced in the vertical-up position, at least
without considerable expertise in control.

If the boy’s sister came along and nudged the balanced broom, he could prob-
ably regain the balance if the nudge were not too big. Furthermore, if the boy’s
parakeet, which happened to be flying at large in the house, flew in and landed on
the broom while the boy was balancing it, he could probably still balance the broom.
Thus the young boy has solved an adaptive control problem for a nonlinear time-
varying system subject to disturbances. He has done this with absolutely no expertise
in control or math. His reasoning process can be easily and logically expressed in
terms of fuzzy systems. The boy might even be able to give a set of linguistic rules
he uses to balance the broom.

Fuzzy identification and control methods are used in many engineering
systems. Aircraft flight control and navigation systems, which have traditionally
used gain scheduling, are now increasingly employing methods of fuzzy control.
Some automobile manufacturers use fuzzy logic to control automatic braking
systems, transmissions, and suspension systems. In process control systems, fuzzy
logic is used to control distillation columns and desalination processes. In the field
of robotics, fuzzy control is used to control end-effector position and path. At least
one appliance manufacturer employs a fuzzy system to control turbidity in washing
machine water, and at least one camera manufacturer ironically uses fuzzy logic in
their autofocus system.

Much is made of the paucity of stability proofs for systems controlled with
fuzzy controllers, although inroads have been made with linear matrix inequalities
(discussed in Chapter 7). It is true that there exist more stability proofs for closed-
loop systems involving conventional nonfuzzy controllers, such as state feedback
controllers, $H_\infty$ controllers, sliding mode controllers, adaptive controllers, and the
like. However, it must be kept in mind that these proofs all assume some model
(or truth model) of the plant being controlled. The true system being controlled is
almost never perfectly described by this truth model; the truth model is at best
only an approximation of the true plant. This means that the stability of the true
plant under state feedback control, $H_\infty$ control, and so on, may not really be guar-
anteed either.

Finally, we point out that when the greatest precision is needed and money
and human life are on the line, automatic control systems, which possess stability
proofs, are often eschewed in favor of “fuzzy” humans, which possess no stability
proofs. The landing of jumbo jets is seldom entrusted to automatic landing systems; a human pilot usually takes over in the vicinity of the airport. Similarly, the final approach and landing of the Space Shuttle is done by astronauts, not autopilots.

1.2 EXPERT KNOWLEDGE

The term “heuristic” refers to knowledge that is acquired by experimentation or trial and error. Each of us has vast stores of heuristic knowledge that we have accumulated over the years to accomplish many tasks. For instance, you may know how to cook spaghetti or play the piano. These skills did not come instantaneously, they came after much practice. On a much more fundamental level, infants learn to speak, walk, and hundreds of other complicated tasks mainly by practice and trial and error.

It is not uncommon that a person can operate a complex process quite well by him/herself using only heuristic knowledge without the aid of any closed-loop control. For instance, an experienced truck driver can back up a semitrailer to a loading dock without any control system helping him. Pilots can land aircraft using only their experience of past landings. Emergency responders can choose the best routes to take through crowded urban areas from years of experience driving in the area. An experienced investment analyst can know which investments have higher or lower probability for success based on past experience.

These are examples of “expert knowledge,” and it is one of the great strengths of fuzzy control to be able to incorporate such knowledge. Incidentally, the term “expert knowledge” is used quite loosely here. For instance, in the above example of a young boy balancing an inverted broom in the palm of his hand, the boy is the “expert.”

Some of the controllers in this book are designed using only expert knowledge. In fact, the first fuzzy controllers were designed using only expert knowledge. Some systems that are too complex to permit analytical model-based controller design are easily controlled with fuzzy controllers designed from expert knowledge.

1.3 WHEN AND WHEN NOT TO USE FUZZY CONTROL

Because we usually deal with real-world systems with real-world constraints (cost, computer resources, size, weight, power, heat dissipation, etc.), it goes without saying that the simplest method to accomplish a task is the one that should be used. PID controllers are used in the vast majority of all industrial controllers. They are simple and cheap to construct from discrete components and are quite effective for many control tasks. On the other hand, fuzzy control is usually fairly complex to implement. Therefore, if a control task can be accomplished with a PID or some equally simple controller, that controller should be used instead of a fuzzy one. If the system to be controlled is linear and time invariant, there are many well-known methods for its control; a fuzzy controller for such a system would be overkill.
CHAPTER 1 INTRODUCTION

The strength of the fuzzy approach is in dealing with complex nonlinear systems with perhaps unknown or poorly known mathematical models. For example, the problem of vehicle routing is not easily handled with standard model-based methods, nor is control of distillation columns or control of power systems. Such complex, nonlinear, time-varying, or unknown or poorly known infinite-dimensional systems, while not amenable to analytical methods, can sometimes be handled using fuzzy methods.

1.4 CONTROL

Control is the discipline of forcing a plant to behave as desired [1–3]. The three control objectives addressed in this book are stabilization, tracking, and model following. In stabilization, the control objective is to add or enhance stability. In tracking, the objective is to force the plant output to track a desired reference signal. In model following, the control objective is to force the plant to emulate a reference model that possesses certain qualities desired for the plant.

For an example of stabilization, consider the gantry shown in Figure 1.1.

The gantry consists of a motorized cart on which is mounted a rigid rod that is free to rotate without friction. The cart moves in one dimension along a track. A typical gantry control objective is to move the cart from location to location along the track with a minimum of rod sway. A practical application of this is found in industry. Industrial gantries are used to move heavy objects from place to place in a building or yard so that they can be worked on or serviced by different machines. It is generally desired that the load sway as little as possible during the movement.

The gantry is open-loop stable since if the rod is displaced from the vertical-down position it will eventually return to it. However, this may take an unacceptably long time because the gantry has very little damping. Therefore, even though the gantry is theoretically stable as it is, we can design a controller to increase the gantry’s stability, that is, increase the damping so that oscillations die out more quickly. Large industrial gantries usually use either some type of closed-loop control or an operator with expert knowledge of how to minimize the oscillations.
1.4 CONTROL

For another example of stabilization, consider the inverted pendulum of Figure 1.2.

![Inverted pendulum](image)

The inverted pendulum consists of a motorized cart on which is mounted a rigid rod that is free to rotate without friction. The cart moves in one dimension along a track.

The inverted pendulum is open-loop unstable (i.e., in the absence of external control), if the rod is displaced from the vertical-up position it will fall down and never return to vertical-up. Some type of closed-loop control is necessary to maintain the rod in the vertical-up position. The stabilization of the inverted pendulum with a fuzzy controller is addressed in Chapter 4.

A practical application of the inverted pendulum is found in rocketry. A rocket immediately after launch, being long and slim, tends to fall over without some type of closed-loop control to keep it vertical. In large modern rockets, there are several subsystems to accomplish this. One is a closed-loop control system to actuate the base of the rocket so that it always moves underneath the rocket’s nose. This is essentially a two-dimensional version of the inverted pendulum problem.

For an example of tracking, consider the ball and beam system of Figure 1.3.

![Ball and beam system](image)

In this system, the shaft of a direct current (DC) motor is attached to the center of a beam along which a ball can roll. When power is supplied to the motor, the beam rotates in the vertical plane, causing the ball to roll along it.

The ball and beam is open-loop unstable (i.e., if the ball is displaced from its initial position, it will not return to it without some type of closed-loop control). A
tracking control objective would be to actuate the motor so the ball follows a predetermined path at a desired velocity along the beam. The tracking problem for the ball and beam is addressed in Chapter 10.

For a practical example of tracking, consider an annealing furnace whose temperature must accurately follow a certain temperature profile in order to properly anneal certain metals. This can be a difficult task for an inexperienced operator, so closed-loop control is usually used to control the furnace temperature accurately.

For an example of model following, consider the motor-driven robotic link of Figure 1.4.

This consists of a DC motor with a rigid rod attached to its shaft. The motor shaft (hence the link) can be rotated through 360°. A true industrial robot might consist of several of these links connected in series (with a second motor and link located at the end of the first link, etc.).

The system is open-loop unstable, that is, if the link is displaced from its initial angle, it will not return to it without some type of closed-loop control (unless the initial angle was vertical-down). A model following control objective would be to actuate the motor so the input–output behavior of the link emulates that of a reference model specified by the designer. The model following problem for the motor-driven robotic link is addressed in Chapter 10.

For a practical example of model following, consider a small airplane being used as a trainer for jumbo jet pilots. A model following control system can be designed to make the small plane handle like a jumbo jet, thus obviating the need to use large and expensive airplanes to train pilots.

1.5 INTERCONNECTION OF SEVERAL SUBSYSTEMS

The identification and control schemes in this book involve interconnections of several subsystems. The best way to describe these is to draw a picture called a block diagram showing blocks for each subsystem with lines labeled with the names of the signals they contain interconnecting them. The diagrams of Figures 1.1–1.4 are
visually descriptive (they show what the systems look like physically), but not very efficient for showing interconnections between systems.

For instance, consider the gantry of Figure 1.1. Its single input is the force $F$ delivered to the cart, and its output is the rod angle $\psi$. To depict an interconnection involving the gantry and other subsystems, it is not important what the gantry looks like physically, only its inputs and outputs. Therefore, if the gantry is to be depicted in an interconnection of subsystems, it would be more efficiently represented by the block shown in Figure 1.5. This block shows all pertinent quantities for interconnection, that is the gantry input $F(t)$ and the output $\psi(t)$.

![Figure 1.5. Block diagram of gantry.](image)

If we desire to precisely control the gantry, it generally must be placed in some type of feedback configuration. One of the two most basic feedback configurations is the cascade connection with unity feedback. The gantry in a unity feedback configuration is shown in Figure 1.6.

![Figure 1.6. Cascade configuration.](image)

Figure 1.6 shows the gantry with its output $\psi(t)$ measured and fed back with negative polarity to one input of a summer. Because $\psi$ is the rod angle, to measure it requires a sensor that can measure angles, perhaps a potentiometer, encoder, resolver, etc. attached to the gantry. The signal actually fed back to the summer is a voltage from the angle sensor that is indicative of the rod angle.

The other summer input is an external reference signal $r(t)$ that may be supplied by the designer as a signal for the gantry angle to follow. Because we desire $\psi(t)$ to follow $r(t)$, $r(t)$ is sometimes called the command or reference input. If it is desired that the gantry rod hang vertically downward and motionless, $r(t)$ would be zero.

The summer output is the difference $e(t) = r(t) - \psi(t)$. It is the error between the command $r(t)$ and the gantry angle $\psi(t)$. The tracking error $e(t)$ forms the input to a cascade compensator designed to minimize $e$. The compensator output is a voltage proportional to the force that is to be delivered to the gantry. This voltage is delivered to the cart motor that applies the prescribed force to the gantry. If the compensator is properly designed, this closed-loop system will result in $\psi(t) \rightarrow r(t)$.
as \( t \to \infty \) (i.e., asymptotic tracking). Since in this book the controllers are fuzzy, the cascade compensator block in Figure 1.6 will be a fuzzy system.

1.6 IDENTIFICATION AND ADAPTIVE CONTROL

In the context of control, identification refers to the determination of a plant model that is sufficient to enable the design of a controller for the plant. Identification of linear time invariant systems is straightforwardly done using conventional methods [4], hence fuzzy identification techniques are not necessary for such systems. Fuzzy techniques are useful for the identification of nonlinear systems. Identification of nonlinear systems is much less well defined than the linear case, especially if the form of the nonlinearity is not known. Since fuzzy control is not model based, it is not necessary to assume any particular form of the nonlinearity.

The identifier takes measurements of the plant input and output, and from these determines a model for the plant. The fact that the plant is nonlinear is not a problem if the identifier is fuzzy because fuzzy systems are in general nonlinear. A block diagram depicting fuzzy identification of the gantry is shown in Figure 1.7.

In Figure 1.7, the force delivered to the gantry (or perhaps compensator output voltage) is measured, as is the gantry rod angle. These two signals, which are voltages, are fed to the identifier, which operates on them to obtain a mathematical model of the gantry. Identification is addressed in Chapter 9.

The latter chapters of this book are concerned with adaptive fuzzy control. Adaptive control is a method by which the system behavior is monitored online in real time and the control continually updated and adjusted to adapt to uncertainties or changes in the plant. There are two basic types of adaptive control: indirect and direct. In indirect adaptive control, the plant is continually identified online, and at each time step during the process, the controller is adjusted based on this identification. This situation is depicted in Figure 1.8. In Figure 1.8, the arrow from the identifier going through the compensator indicates that the compensator is being adjusted in real time by the current mathematical model of the gantry determined by the identifier. In direct adaptive control, which is not depicted here, the parameters of the controller are
directly adjusted rather than going through the intermediate step of identification. Direct and indirect adaptive control are addressed in Chapter 10.

![Figure 1.8. Indirect adaptive control of gantry.](image)

Note that block diagrams are not used in the remainder of this book. They are only mentioned here to give the reader some idea of how the various systems in the examples are interconnected for identification and control.

## 1.7 SUMMARY

Fuzzy logic is an attempt to mimic the human reasoning process. Fuzzy logic can be used to identify and control complicated systems that would be difficult or impossible to control by any other means. Expert knowledge is knowledge possessed by human experts about a situation or problem. Expert knowledge, although invaluable in solving complicated problems, cannot be utilized by conventional model-based controllers. However, it is one of the great strengths of fuzzy control that expert knowledge can be easily incorporated into fuzzy controllers.

Fuzzy identification and control is computer-intensive. Therefore, fuzzy methods should be used only when simpler and cheaper methods, such as PID control, cannot accomplish the control task. Fuzzy methods should generally not be used to identify or control linear time invariant systems, as there are many well-established methods for doing this.

The three control objectives addressed in this book are stabilization, tracking, and model following. A system is stable if its response to bounded inputs is bounded, or if it returns to an equilibrium state if displaced from it. The stabilization control objective could involve stabilizing an unstable system, or increasing the stability of an insufficiently stable system. The tracking control objective entails forcing a system’s output to track a given reference signal. The model following control objective entails forcing a system to emulate a reference model specified by the designer. The stabilization, tracking, and model following control objectives will be accomplished in this book with fuzzy identifiers and controllers.

Block diagrams are introduced in this chapter only to provide a concise illustration of the way the fuzzy identifiers and controllers in this book will be
interconnected with various example systems. The rest of this book does not contain block diagrams.

EXERCISES

1.1 Give an example of a set of several rules you use to make some decision, for instance, whether to go out or stay in on Saturday night. Your “rule base” should include several rules, not just one.

1.2 Give an example of a set of several rules you use to accomplish some task, for instance deciding how much money to invest in the stock market. Your “rule base” should include several rules, not just one.

1.3 Give five examples of expert knowledge that you possess.

1.4 Give five examples of expert knowledge possessed by someone else of whom you are aware.

1.5 Give two examples of systems controlled by fuzzy logic controllers other than the examples given above. State why fuzzy control is appropriate for their control, and why conventional nonfuzzy control would be inadequate.

1.6 Give two examples of systems controlled by conventional nonfuzzy controllers, and state why fuzzy control would be inappropriate for their control.

1.7 Draw block diagrams of the inverted pendulum, the motor driven robotic link, and the ball and beam.

1.8 Draw a block diagram of the inverted pendulum in a unity feedback configuration with cascade compensator.

1.9 Draw a block diagram of the motor driven robotic link with an attached identifier.

1.10 Draw a block diagram of the ball and beam in a unity feedback configuration with an adjustable cascade compensator being adjusted by an identifier.