Background, Preliminaries and Applications of Fuzzy Logic

Some Preliminaries

Fuzzy logic is a branch of machine intelligence that helps computers paint gray, commonsense pictures of an uncertain world.

Fuzzy logic manipulates such vague concepts as "warm" or "still dirty" and so helps engineers to build air conditioners, washing machines and other devices that judge how fast they should operate or shift from one setting to another even when the criteria for making those changes are hard to define.

When mathematicians lack specific algorithms that dictate how a system should respond to inputs, fuzzy logic can control or describe the system by using "commonsense" rules that refer to indefinite quantities.

No known mathematical model can back up a truck-and-trailer rig from a parking lot to a loading dock when the vehicle starts from a random spot. Both humans and fuzzy systems can perform this nonlinear guidance task by using practical but imprecise rules such as "If the trailer turns a little to the left, then turn it a little to the right."

Fuzzy systems often glean their rules from experts. When no expert gives the rules, adaptive fuzzy systems learn the rules by observing how people regulate real systems.

A recent wave of commercial fuzzy products, most of them from Japan, has popularized fuzzy logic.

In 1980 the contract firm of F. L. Smith and Company in Copenhagen first used a fuzzy system to oversee the operation of a cement kiln. In 1988 Hitachi turned over control of a subway in Sendai, Japan, to a fuzzy system. Since then, Japanese companies have used fuzzy logic to direct hundreds of household appliances and electronics products. The Ministry of International Trade and Industry estimates that in 1992 Japan produced about $2 billion worth of fuzzy products.

Applications for fuzzy logic extend beyond control systems. Recent theorems show that in principle fuzzy logic can be used to model any continuous system, be it based in engineering or physics or biology or economics.

Investigators in many fields may find that fuzzy, commonsense models are more useful or accurate than are standard mathematical ones.

At the heart of the difference between classical and fuzzy logic is something Aristotle called the law of the excluded middle. In standard set theory, an object either does or does not belong to a set. There is no middle ground. In such bivalent sets, an object cannot belong to both a set and its complement set or to neither of the sets. This principle preserves the structure of logic and avoids the contradiction of an object that both is and is not a thing at the same time.

Sets that are fuzzy, or multivalent, break the law of the excluded middle- to some degree. Items belong only partially to a fuzzy set. They may also belong to more than one set. Even to just one individual, the air may feel cool , just right and warm to varying degrees. Whereas the boundaries of standard sets are exact, those of fuzzy sets are curved or taper off, and this curvature creates partial contradictions. The air can be 20 percent cool-and at the same time, 80 percent not cool.

Fuzzy degrees are not the same as probability percentages. Probabilities measure whether something will occur or not. Fuzziness measures the degree to which something occurs or some condition exists. The statement "There is a 30 percent chance the weather will be cool" conveys the probability of cool weather. But “The morning feels 30 per- cent cool" means that the air feels cool to some extent-and at the same time, just right and warm to varying extents.

The only constraint on fuzzy logic is that an object's degrees of membership in complementary groups must sum to unity. If the air seems 20 percent cool, it must also be 80 percent not cool. In this way, fuzzy logic just skirts the bivalent contradiction-that something is 100 percent cool and 100 percent not cool-that would destroy formal logic. The law of the excluded middle holds merely as a special case in fuzzy logic, namely when an object belongs 100 percent to one group.

The modern study of fuzzy logic and partial contradictions had its origins early in this century, when Bertrand Russell found the ancient Greek paradox at the core of modern set theory and logic. According to the old riddle, a Cretan asserts that all Cretans lie. So, is he lying? If he lies, then he tells the truth and does not lie. If he does not lie, then he tells the truth and so lies. Both cases lead to a contradiction because the statement is both true and false. Russell found the same paradox in set theory. The set of all sets is a set, and so it is a member of itself. Yet the set of all apples is not a member of itself because its members are apples and not sets. Perceiving the underlying contradiction, Russell then asked, "Is the set of all sets that are not members of themselves a member of itself ?" If it is, it isn't; if it isn't, it is.

Faced with such a conundrum, classical logic surrenders. But fuzzy logic says that the answer is half true and half false, a 50-50 divide. Fifty percent of the Cretan's statements are true, and 50 percent are false. The Cretan lies 50 percent of the time and does not lie the other half. When membership is less than total, a bivalent system might simplify the problem by rounding it down to zero or up to 100 percent. Yet 50 percent does not round up or down.

In the 1920s, independent of Russell, the Polish logician Jan Lukasiewicz worked out the principles of multivalued logic, in which statements can take on fractional truth values between the ones and zeros of binary logic. In a 1937 article in Philosophy of Science, quantum philosopher Max Black applied multivalued logic to lists, or sets of objects, and in so doing drew the first fuzzy set curves. Following Russell's lead, Black called the sets "vague."

Almost 30 years later Lotfi A. Zadeh published "Fuzzy Sets," a landmark paper that gave the field its name. Zadeh applied Lukasiewicz's logic to every object in a set and worked out a complete algebra for fuzzy sets. Even so, fuzzy sets were not put to use until the mid 1970s, when Ebrahim H. Mamdani of Queen Mary College in London designed a fuzzy controller for a steam engine. Since then, the term "fuzzy logic" has come to mean any mathematical or computer system that reasons with fuzzy sets.

Fuzzy logic is based on rules of the form "if...then" that convert inputs to outputs-one fuzzy set into another. The controller of a car's air conditioner might include rules such as "If the temperature is cool, then set the motor speed on slow" and "If the temperature is just right, then set the motor speed on medium." The temperatures (cool, just right) and the motor speeds (slow, medium) name fuzzy sets rather than specific values.

To build a fuzzy system, an engineer might begin with a set of fuzzy rules from an expert. An engineer might define the degrees of membership in various fuzzy input and output sets with sets of curves. The relation between the Input and Output sets could then be plotted. Given the rule "If the air feels cool, then set the motor to slow," the inputs (temperature) would be listed along one axis of a graph and the outputs (motor speed) along a second axis. The product of these fuzzy sets forms a fuzzy patch, an area that represents the set of all associations that the rule forms between those inputs and outputs.

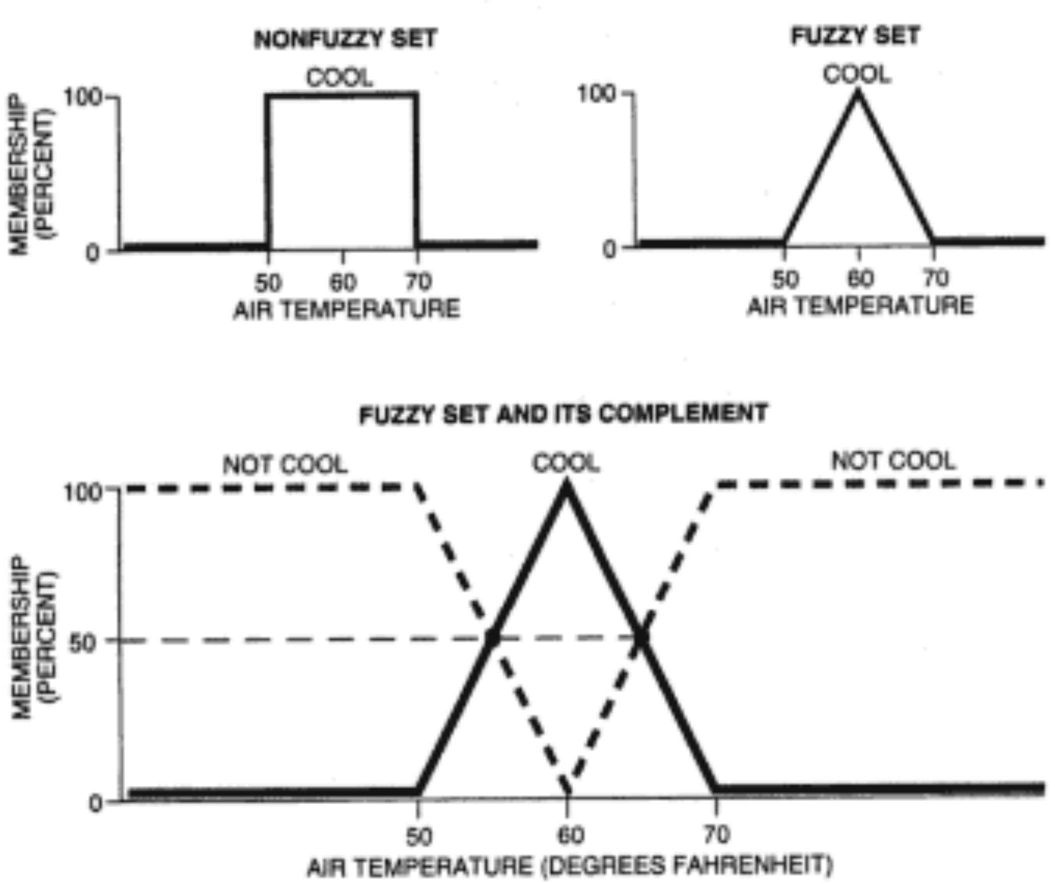
The size of the patch reflects the rule's vagueness or uncertainty. The more precise the fuzzy set, the smaller it becomes. If "cool" is precisely 68 degrees Fahrenheit, the fuzzy set collapses to a spike. If both the cool and slow fuzzy sets are spikes, the rule patch is a point.

The rules of a fuzzy system define a set of overlapping patches that relate a full range of inputs to a full range of outputs. In that sense, the fuzzy system approximates some mathematical function or equation of cause and effect.These functions might be laws that tell a microprocessor how to adjust the power of an air conditioner or the speed of a washing machine in response to some fresh measurement.

Fuzzy systems can approximate any continuous math function. Kosko proved this uniform convergence theorem by showing that enough small fuzzy patches can sufficiently cover the graph of any function or input/ output relation. The theorem also shows that we can pick in advance the maximum error of the approximation and be sure there is a finite number of fuzzy rules that achieve it. A fuzzy system reasons, or infers, based on its rule patches. Two or more rules convert any incoming number into some result because the patches overlap. When data trigger the rules, overlapping patches fire in parallel-but only to some degree.

Imagine a fuzzy air conditioner that relies on five rules and thus five patches to match temperatures to motor speeds. The temperature sets (cold, cool, just right, warm and hot) cover all the possible fuzzy inputs. The motor speed sets (very slow, slow, medium, fast and very fast) describe all the fuzzy outputs. A temperature of, say, 68 degrees F might be 20 percent cool (80 percent not cool) and 70 percent just right (30 percent not just right). At the same time, the air is also 0 percent cold, warm and hot. The "if cool" and "if just right" rules would fire and invoke both the slow and medium motor speeds.

The two rules contribute proportionally to the final motor speed. Because the temperature was 20 percent cool, the curve describing the slow engine speed must shrink to 20 percent of its height. The "medium" curve must shrink to 70 percent. Summing those two reduced curves produces the final curve for the fuzzy output set.



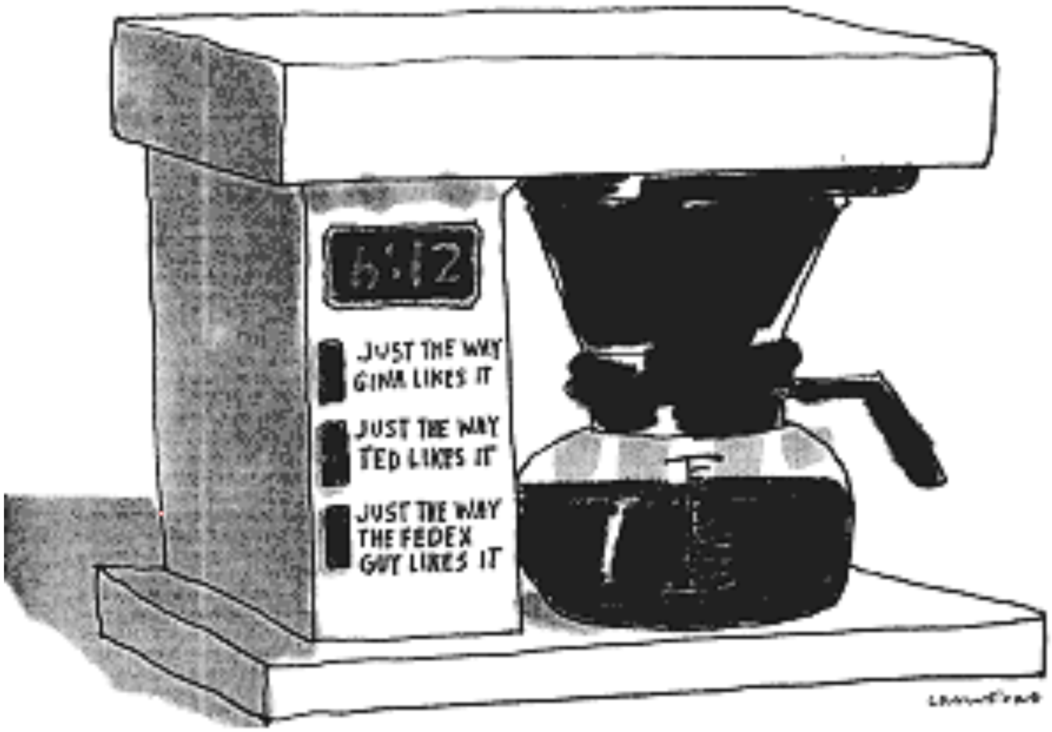
Set Theory underlies the difference between standard and fuzzy logic. In standard logic, objects belong to a set fully or not at all (top left).Objects belong to a fuzzy set only to some extent (top right) and to the set's complement
to some extent. Those partial memberships must sum to unity (bottom).If
55 degrees is 50 percent "cool," it is also 50 percent "not cool."

In its fuzzy form, such an output curve does not assist controllers that act on binary instructions. So the final step is a process of defuzzification, in which the fuzzy output curve is turned into a single numerical value. The most common technique is to compute the center of mass, or centroid, of the area under the curve. In this instance, the centroid of the fuzzy output curve might correspond to a motor speed of 47 revolutions per minute. Thus, beginning with a quantitative temperature input, the electronic controller can reason from fuzzy temperature and motor speed sets and arrive at an appropriate and precise speed output.

All fuzzy systems reason with this fire-and-sum technique-or something close to it. As systems become more complex, the antecedents of the rules may include any number of terms conjoined by "and" or disjoined by "or." An advanced fuzzy air conditioner might use a rule that says, "If the air is cool and the humidity is high, then set the motor to medium."

Fuzzy products use both microprocessors that run fuzzy inference algorithms and sensors that measure changing input conditions. Fuzzy chips are microprocessors designed to store and process fuzzy rules. In 1985 Masaki Togai and Hiroyuki Watanabe, then working at AT & T Bell Laboratories, built the first digital fuzzy chip. It processed 16 simple rules in 12.5 microseconds, a rate of 0.08 million fuzzy logical inferences per second. Togai InfraLogic, Inc., now offers chips based on Fuzzy Computational Acceleration hardware that processes up to two mil1ion rules per second. Most microprocessor firms currently have fuzzy chip research projects. Fuzzy products largely rely on standard microprocessors that engineers have programmed with a few lines of fuzzy inference code. Although the market for dedicated fuzzy chips is still tiny, the value of microprocessors that include fuzzy logic already exceeds $ 1 billion.

There are countless applications for fuzzy logic. The items in this list are more common applications that one may encounter in everyday life.



Subway Car Controller

The most famous fuzzy application is the subway car controller used in Sendai, which has outperformed human operators and conventional automated controllers. Conventional controllers start or stop a train by reacting to position markers that show how far the vehicle is from a station. The controllers are rigidly programmed and the ride jerky; the automated controller will apply the same brake pressure when a train is, say, 100 meters from a station, even if the train is going uphill or downhill. In the mid-l980s engineers from Hitachi used fuzzy rules to accelerate, slow and brake the subway trains more smoothly than could a deft human operator.

Subway Car Controller (Cont.)

The rules encompassed a broad range of variables about the ongoing performance of the train, such as how frequently and by how much its speed changed and how close the actual speed was to the maximum speed. In simulated tests the fuzzy controller beat an automated version on measures of riders' comfort, shortened riding times and even achieved a 10 percent reduction in the train's energy consumption. Today the fuzzy system runs the Sendai subway during peak hours and runs some Tokyo trains as well. Humans operate the subway during nonpeak hours to keep up their skills.

Bus Timetables

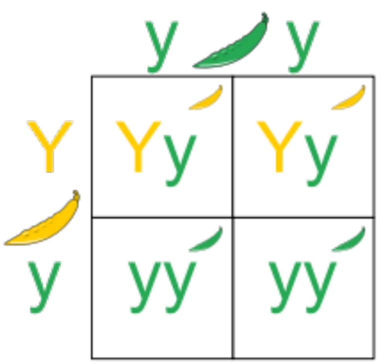
How accurately do the schedules predict the actual travel time on the bus?

Bus schedules are formulated on information that does not remain constant. They use fuzzy logic because it is impossible to give an exact answer to when the bus will be at a certain stop. Many unforseen incidents can occur. There can be accidents, abnormal traffic backups, or the bus could break down. An observant scheduler would take all these possibilities into account, and include them in a formula for figuring out the approximate schedule. It is that formula which imposes the fuzziness.

Predicting Genetic Traits:

Genetic traits are a fuzzy situation for more than one reason. There is the fact that many traits can't be linked to a single gene. So only specific combinations of genes will create a given trait. Secondly, the dominant and recessive genes that are frequently illustrated with Punnet squares, are sets in fuzzy logic. The degree of membership in those sets is measured by the occurrence of a genetic trait. In clear cases of dominant and recessive genes, the possible degrees in the sets are pretty strict. Take, for instance, eye color. Two brown-eyed parents produce three blue-eyed children. Sounds impossible, right? Brown is dominant, so each parent must have the recessive gene within them.

Their membership in the blue eye set must be small, but it is still there. So their children have the potential for high membership in the blue eye set, so that trait actually comes through. According to the Punnet square, 25% of their children should have blue eyes, with the other 75% having brown. But in this situation, 100% of their children have the recessive color. Was the wife being unfaithful with that nice, blue-eyed salesman? Probably not. It's just fuzzy logic at work.



Punnett square showing a typical monohybrid

The Punnett square is a diagram that is used to predict an outcome of a particular cross or breeding experiment. It is named after Reginald C. Punnett, who devised the approach, and is used by biologists to determine the probability of an offspring having a particular genotype. The Punnett square is a summary of every possible combination of one maternal allele with one paternal allele for each gene being studied in the cross

Temperature Control (heating/cooling)

The trick in temperature control is to keep the room at the same temperature consistently. Well, that seems pretty easy, right? But how much does a room have to cool off before the heat kicks in again? There must be some standard, so the heat (or air conditioning) isn't in a constant state of turning on and off. Therein lies the fuzzy logic. The set is determined by what the temperature is actually set to. Membership in that set weakens as the room temperature varies from the set temperature. Once membership weakens to a certain point, temperature control kicks in to get the room back to the temperature it should be.

Auto-focus on a Camera

Auto-focus cameras are a great revolution for those who spent years struggling with "old-fashioned" cameras. These cameras somehow figure out, based on multitudes of inputs, what is meant to be the main object of the photo. It takes fuzzy logic to make these assumptions. Perhaps the standard is to focus on the object closest to the center of the viewer. Maybe it focuses on the object closest to the camera. It is not a precise science, and cameras err periodically. This margin of error is acceptable for the average camera owner, whose main usage is for snapshots. However, the "old-fashioned" manual focus cameras are preferred by most professional photographers. For any errors in those photos cannot be attributed to a mechanical glitch. The decision making in focusing a manual camera is fuzzy as well, but it is not controlled by a machine.

Medical Diagnosis

How many of what kinds of symptoms will yield a diagnosis? How often are doctors in error?

Surely everyone has seen those lists of symptoms for a horrible disease that say "if you have at least 5 of these symptoms, you are at risk". It is a hypochondriac's haven. The question is, how do doctors go from that list of symptoms to a diagnosis? Fuzzy logic. There is no guaranteed system to reach a diagnosis. If there were, we wouldn't hear about cases of medical misdiagnosis. The diagnosis can only be some degree within the fuzzy set.

Predicting Travel Time

This is especially difficult for driving, since there are plenty of traffic situations that can occur to slow down travel.

As with bus timetabling, predicting ETA's is a great exercise in fuzzy logic. That's why it is called an estimated time of arrival. A major player in predicting travel time is previous experience. *It took me six hours to drive to Philadelphia last time, so it should take me about that amount of time when I make the trip again.* Unfortunately, other factors are not typically considered. Weather, traffic, construction, accidents should all be added into the fuzzy equation to deliver a true estimate.

Antilock Braking System

It's probably something you hardly think about when you're slamming on the brakes in your car

The point of an ABS is to monitor the braking system on the vehicle and release the brakes just before the wheels lock. A computer is involved in determining when the best time to do this is. Two main factors that go into determining this are the speed of the car when the brakes are applied, and how fast the brakes are depressed. Usually, the times you want the ABS to really work are when you're driving fast and slam on the brakes. There is, of course, a margin for error. It is the job of the ABS to be "smart" enough to never allow the error go past the point when the wheels will lock. (In other words, it doesn't allow the membership in the set to become too weak.)

Generalities

Companies in Japan and Korea are building an array of fuzzy consumer goods that offer more precise control than do conventional ones. Fuzzy washing machines adjust the wash cycle to every set of clothes, changing strategies as the clothes become clean. A fuzzy washing machine gives a finer wash than a "dumb" machine with fixed commands. In the simplest of these machines, an optical sensor measures the murk or clarity of the wash water, and the controller estimates how long it would take a stain to dissolve or saturate in the wash water. Some machines use a load sensor to trigger changes in the agitation rate or water temperature. Others shoot bubbles into the wash to help dissolve dirt and detergent. A washing machine may use as few as 10 fuzzy rules to determine a wide variety of washing strategies.

Generalities (cont.)

In cameras and camcorders, fuzzy logic links image data to various lens settings. One of the first fuzzy camcorders, the Canon hand-held H800, which was introduced in 1990, adjusts the autofocus based on 13 fuzzy rules. Sensors measure the clarity of images in six areas. The rules take up about a kilobyte of memory and convert the sensor data to new lens settings. Matsushita relies on more rules to cancel the image jitter that a shaking hand causes in its small Panasonic camcorders. The fuzzy rules infer where the image will shift. The rules heed local and global changes in the image and then compensate for them. In contrast, camcorder controllers based on mathematical models can compensate for no more than a few types of image jitter.

Generalities (cont.)

Systems with fuzzy controllers are often more energy efficient because they calculate more precisely how much power is needed to get a job done. Mitsubishi and Korea' s Samsung report that their fuzzy vacuum cleaners achieve more than 40 percent energy savings over nonfuzzy designs. The fuzzy systems use infrared light-emitting diodes to measure changes in dust flow and so to judge if a floor is bare. A four-bit microprocessor measures the dust flow to calculate the appropriate suction power and other vacuum settings.

Generalities (cont.)

Automobiles also benefit from fuzzy logic. General Motors uses a fuzzy transmission in its Saturn. Nissan has patented a fuzzy antiskid braking system, fuzzy transmission system and fuzzy fuel injector. One set of fuzzy rules in an on-board microprocessor adjusts the fuel flow. Sensors measure the throttle setting, manifold pressure, radiator water temperature and the engine's revolutions per minute. A second set of fuzzy rules times the engine ignition based on the revolutions per minute, water temperature and oxygen concentration.

One of the most complex fuzzy systems is a model helicopter designed by Michio Sugeno of the Tokyo Institute of Technology. Four elements of the craft-the elevator, aileron, throttle and rudder-respond to 13 fuzzy voice commands, such as "up," "land" and "hover." The fuzzy controller can make the craft hover in place, a difficult task even for human pilots.

Generalities (cont.)

A few fuzzy systems manage information rather than devices. With fuzzy logic rules, the Japanese conglomerate Omron oversees five medical data bases in a health management system for large firms. The fuzzy systems use 500 rules to diagnose the health of some 10,000 patients and to draw up personalized plans to help them prevent disease, stay fit and reduce stress. Other companies have built trading programs for bonds or stock funds that use fuzzy rules.

The Achilles' heel of a fuzzy system is its rules. All the fuzzy consumer products rely on rules supplied by an expert. Engineers engage in a lengthy process of tuning those rules and the fuzzy sets. To automate this process, some engineers are building adaptive fuzzy systems that use neural networks to refine or even form those initial rules.

Generalities (cont.)

Neural networks are collections of "neurons" and "synapses" that change their values in response to inputs from surrounding neurons and synapses. The neural net acts like a computer be- cause it maps inputs to outputs. The neurons and synapses may be silicon components or equations in software that simulate their behavior. A neuron adds up all the incoming signals from other neurons and then emits its own response in the form of a number. Signals travel across the synapses, which have numerical values that weight the flow of neuronal signals. When new input data fire a network's neurons, the synaptic values can change slightly. A neural net "learns" when it changes the value of its synapses.

Generalities (cont.)

Depending on the available data, networks can learn patterns with or without supervision. A supervised net learns by trial and error, guided by a teacher. A human may point out when the network has erred-when it has emitted a response that differs from the desired output. The teacher will correct the responses to sample data until the network responds correctly to every input.

Supervised networks tune the rules of a fuzzy system as if they were synapses. The user provides the first set of rules, which the neural net refines by running through hundreds of thousands of inputs, slightly varying the fuzzy sets each time to see how well the system performs. The net tends to keep the changes that improve performance and to ignore the others.

Generalities (cont.)

A handful of products in Japan now use supervised neural learning to tune the fuzzy rules that control their operation. Among them are Sanyo' s microwave oven and several companies' washing machines. Sharp employs this technique to modify the rules of its fuzzy refrigerator so that the device learns how often its hungry patron is likely to open the door and adjusts the cooling cycle accordingly. So far the neural net must learn "off-line" in the laboratory, from small samples of behavior by average customers.

Concluding Remarks

If you know what I mean

A poet should be of the
        old-fashioned meaningless brand:
obscure, esoteric, symbolic,
        -- the critics demand it;
so if there's a poem of mine
        that you do understand
I'll gladly explain what it means