to the roadway. The model predicts that the pollutants will concentrate immediately above and adjacent to the roadway, but the two experiments show that this is not the case. David Chock of GM has developed a new mathematical model that takes into account what was learned in the GM study and is now working on others that incorporate results from both studies.

Perhaps more important is the fact that the catalysts are not oxidizing as much of the sulfur as they were expected to. This discrepancy results, according to Ronald L. Bradow of EPA, from the way in which the original tests were run. In those first studies, concentrations of sulfuric acid were measured in the exhaust of cars running at constant speeds for long periods. This procedure gives erroneously high results when extrapolated to conditions on roadways.

When the motor is run at constant speeds, there are very small concentrations of carbon monoxide and hydrocarbons in the exhaust gases passing over the catalyst and as much as 85 percent of the sulfur can, in fact, be oxidized. But the resulting sulfuric acid, Bradow says, initially remains bound to the catalyst in the form of aluminum sulfates. As the rather substantial capacity of the catalyst is reached, high concentrations of acid begin to appear in the exhaust—a condition that was met in the constant speed tests.

Normal driving conditions entail frequent periods of acceleration and deceleration, even on the open highway. During these periods, the concentrations of hydrogen, carbon monoxide, and hydrocarbons passing over the catalyst increase, and reducing conditions are created. The catalyst-bound sulfate is reduced to sulfur dioxide under these conditions and released from the catalyst. Tests at many different facilities on large numbers of new cars subjected to driving

Speaking of Science

Mathematics and Magic: Illumination and Illusion

Superficially, mathematics and magic seem antithetical. Good magicians successfully hide their methods to maintain illusions. Good mathematicians illuminate their methods. Magicians perform for the public and hope for both public acclaim and admiration by other magicians. Mathematicians generally concentrate on impressing only a small group of people in their own area of specialization. Typical of many mathematicians' views is that of Fritz John of the Courant Institute of New York University. John proclaimed that he sought neither fame nor fortune but only "the grudging admiration of a few close friends."

In certain cases, however, an understanding of both mathematics and magic can lead to unique ways to analyze results of experimental research. Statisticians often acknowledge the fact that unexpected subjective elements may affect results of experiments and their own attempts to analyze data, but few are experts at ferreting out where and how these elements occur. One statistician—32-year-old Persi Diaconis of Stanford University—is unusually skilled at this sort of analysis. Diaconis is well versed in the art of illusion since he spent 12 years as a professional magician before becoming a mathematician.

Diaconis is so talented as a magician that other experts rank him among the top three magicians in the world for close-up tricks (such as card tricks). As a sideline, he spent the past 10 years analyzing parapsychology experiments and debunking so-called psychics. His experiences as a magician played a major role in his decision to become a mathematician, and now those experiences aid him in devising ways to account for often inadvertent subjectivity in analyses of experimental results. Diaconis' thoughts on why he became a magician and how his life as a mathematician is affected by his knowledge of magic illustrate why he is uniquely qualified for his current research.

Diaconis' interest in magic goes back to his childhood—he says he did his first magic tricks at the age of 5. Something of a child prodigy, he progressed quickly through school and entered City College of New York when he was 14. However, he soon dropped out of college and ran away from home to become a professional magician. After working for a while with magicians James Randi (The Amazing Randi) and Day Vernon, Diaconis struck out on his own at the age of 17 and built a considerable reputation. He studied magic seriously during this period, visiting other magicians and collecting books. Diaconis estimates that he now has 2000 to 3000 books on magic.

By the time Diaconis was 24, the lonely life of a magician began to wear on him, and he went back to college with the stated aim of gaining a classical education. While at college this time, he was lured into mathematics. His interest in mathematics grew from his days as a magician, when he made up magic tricks based on mathematical principles, tried to analyze gambling strategies, and was consulted on the design of experiments on extrasensory perception. Those experiments, he points out, often require sophisticated statistics for their analysis.

When Diaconis finished college he entered the Ph.D. program in statistics at Harvard University. Because he wanted to succeed in graduate school on his own merits, Diaconis carefully kept quiet about his previous life in show business. When he obtained his degree and accepted a job at Stanford, however, he found out that the game was up. *Time* wrote a story about him, which Diaconis found posted on Stanford's bulletin boards. After that, says Diaconis, "I thought it was time to come out of the closet."

Although he still practices magic for about an hour each day and still gives an occasional show, Diaconis stresses that he would rather be known for his research interests and accomplishments than for his magic. He was recently embarrassed as a result of an incident that occurred when he did a show for the Air Force. The local newspapers wrote about him, and their stories were picked up by Associated Press under the head "Prof. Does Magic."

A quiet, unpretentious man who seems to move in slow motion, Diaconis bears little resemblance to the stereotypical glib entertainer who is skilled at sleight of hand. He admits that when he made his living as a magician, he learned to take control of a conversation by telling anecdotes. But, he says, "It's a relief to get away from all that now—to be a more-or-less anonymous member of a group rather than always trying to be the center of attention."

When asked how his experiences as a magician bear on cycles similar to those that might be encountered on a freeway show that the average new car equipped with a catalytic converter and an air pump oxidizes about 10 to 15 percent of the sulfur in the fuel. Similar cars without air pumps oxidize 7 to 10 percent of the sulfur.

The catalyst's ability to oxidize sulfur, furthermore, appears to deteriorate much more rapidly than its ability to oxidize other pollutants. Tests in California on consumer-owned cars equipped with catalytic converters and air pumps indicate that the oxidation rate for sulfur is reduced to about 5 to 6 percent after 10,000 to 15,000 miles of operation, with little deterioration in the ability of the catalyst to oxidize pollutants. This is probably one of the factors that produce the apparent differences between the LACS and GM studies, since the latter tested primarily new cars.

Most air pollution investigators now seem to agree with EPA that sulfuric acid emissions are not a problem. Pierson, for example, has made some independent calculations that lend credence to the LACS results. Several studies have shown, for example, that the total output of sulfur compounds in the average car is about 30 mg/km and the average output of lead from those cars using leaded fuel is about 24 mg/km. The ratio of sulfur to lead is thus about 1.2. Measurements at the LACS site yield about the same ratio when corrections are made to account for the fact that only 70 percent of the cars use leaded gasoline. In a similar fashion, when the total amount of sulfuric acid produced by cars at the LACS site is divided by the total amount of sulfur compounds produced by the cars—again, corrected to reflect the number of cars equipped with catalysts—the ratio implies an average conversion rate of sulfur to sulfuric acid of 13 percent, in relatively close agreement with actual measurements on production

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his life as a mathematician, Diaconis gives numerous examples. In one case, he noticed that experimenters often let psychics know, directly or inadvertently, whether they are guessing cards correctly. This is not so surprising, he points out, since people constantly pass nonverbal signals to each other through such things as changes in their tones of voice or body movements. In fact, this nonverbal communication forms the basis of a well-known magic act. One performer, for example, asks to have his check in payment for a show hidden in the auditorium in full view of his audience. He then comes on stage and finds the check by reading the nonverbal cues of the audience as he wanders closer to or farther from the check. "It's like the children's game of Hot and Cold," Diaconis says.

Diaconis' observations of the communications between psychics and experimenters led him to ask how much usable information is being transmitted in this way and what the best guessing strategy is. This is an especially important problem since it arises in many contexts other than parapsychology. For example, it has come up in clinical trials in ophthalmology. These trials involve tests of the participants' visual acuity. Some observers have noted that researchers often unconsciously give the participants hints about whether they are guessing correctly when they try to read the letters on the eye charts.

The problem of accounting for such feedback also arises in fields such as forecasting. For example, economists need some way of judging models for forecasting the economy. They must take into account the fact that they know what has happened in the past. Weather forecasters and those who try to forecast air pollution have similar problems. Diaconis points out that analyzing these guessing experiments with feedback is a difficult problem in combinatorics and statistics. Recently he and Ronald Graham, a mathematician at Bell Laboratories, Murray Hill, New Jersey, who specializes in combinatorics, came up with a scoring statistic which they believe provides an improved way to decide whether guesses under conditions with feedback are better than could be obtained by chance.

Diaconis' skill at detecting the differences between what people see and what they think they see aids him in studying a major problem in statistics. The problem arises in data analysis, which Diaconis describes as the drawing of pictures in order to make sense of data. Investigators often want to find some particular relation or trend in a set of data, and if there is any indication that what they seek might be there, they fixate on it. Subjective judgments, then, often creep into statistical analyses.

In classical statistics, according to Diaconis, these subjective judgments are ignored. However, many statisticians are now not only acknowledging such subjectivity but are trying to account for it. Diaconis is drawing on his ability to detect observers' biases in order to study his problem. He is analyzing how an observer's beliefs can be quantified and built into an analysis of data. His goal, he says, is to strike the right balance between a free and innovative interpretation of data and an objective, mathematical analysis.

Diaconis stresses that not all of his inspiration comes from his days as a magician. He works on standard problems in theoretical statistics as well as problems related to magic and extrasensory perception, and spends a quarter of his time on problems suggested by physicists at the Stanford Linear Accelerator, which involve the analysis of data described in many dimensions. Like other statisticians, he is motivated by particular problems that researchers in other fields bring him as well as by the inner beauty and consistency of the mathematics.

Diaconis has few regrets about his decision to become a mathematician. "I'll probably never be as famous a mathematician as I was a magician," he confesses. "And I'll never make as much money. A good magician can easily earn $1000 a day working at conventions." However, he finds the intellectual challenge of doing mathematics greater than that of inventing magic tricks. He enjoys the free interchange of ideas with his colleagues, and he appreciates the dignity of his academic life. In fact, he says, "If magic were performed in a dignified atmosphere for appreciative audiences, I probably would never have left the field. Too often you end up playing for drunks in casinos."

Diaconis, however, cannot escape his unusual history and cannot ignore the fact that it makes him stand out among mathematicians. As Frederick Mosteller, of Harvard University, points out, magicians have unique views about perception—ideas about what people observe and what they think they need to observe. "Magicians, more than most people, can easily accept or raise the possiblity that the conditions of an investigation are very different from what they are reported to be," he says. This perspective can be extremely valuable to a statistician who helps researchers analyze their experiments, as Diaconis' career points out.—Gina Bari Kolata