

studies show that ILP can bring a maximum overall improvement of 2 to 8 times, and even that may be difficult to obtain," says Thomas Gross of Carnegie-Mellon University who has helped design ILP-based processors. "The people who claim there is more parallelism than that available simply haven't been able to prove it."

The trouble with proving anything about ILP, Gross notes, is the lack of a universally accepted benchmark for ILP processor performance. For tasks such as image processing, where the same instructions are carried out independently on many separate chunks of data, he says, ILP is already achieving the kind of speedups Fisher is talking about. But Gross suspects that for applications lacking such repetition, such as word processing, ILP could even be slower than standard sequential computing, owing to the added calculational overhead.

In any case, Gross asserts that efforts to wring the last ounce of parallelism from existing programs by ILP may be wasted in view of the much greater potential of true parallel computing. "Even if you were able to get a 20-times speed improvement over a wide range of programs," he says, "it would still be small compared with the improvement you could get with multiprocessor parallel computing."

David Gelernter, a Yale University computer scientist who researches ways of linking workstations in parallel networks, echoes that assessment. ILP should be seen not as an alternative to general purpose parallel computing but as an adjunct to it, he says. "If ILP can make the workstations in a network faster, that's great," he says. "But if you're talking about going with ILP instead of a network, forget it. In the final analysis the fastest machine will always be 2 or 100 or N of something tied together." As for the difficulties of rewriting conventional software for large-scale parallelism, Gelernter claims they have been greatly exaggerated.

Fisher is unfazed by such indifference to ILP. He thinks Gelernter and others are underestimating the challenge of converting code to parallel networks. And even if that obstacle is cleared away earlier than he expects, he thinks it's silly to worry that hopes for ILP will keep people from pursuing full-scale parallel processing. For a user with access only to a single workstation, he points out, ILP is the only road to parallelism. Worrying about a conflict, he says, "is a little like saying a car that corners better is dangerous because it might keep people from taking an airplane when they want to get across the country." ■ **DAVID H. FREEDMAN**

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Hydroxyl, the Cleanser That Thrives on Dirt

Pollution may have reduced this atmospheric cleanser, but half-measures against pollution might make matters worse

THE HYDROXYL RADICAL IS THE PAC MAN OF Earth's atmosphere. Brought to life by a zap of solar radiation, this molecule of hydrogen and oxygen spends the second or so before it flickers out of existence scooting about gobbling up most anything that has been fouling the air—carbon monoxide that leads to smog, methane that enhances the greenhouse, sulfurous gases, and unburned oil. By oxidizing and thus eliminating these contaminants, the voracious hydroxyl serves as the mainstay of the global atmosphere's self-cleansing process, holding at bay noxious gases produced by natural processes and, more recently, doing its best to mitigate the worst excesses of human activity. It's no surprise, then, that hydroxyl has probably lost some of its zip of late.

In the face of the mounting load of atmospheric pollutants, the molecular super-cleanser's lifetime seems to have gotten even shorter, with little compensating speedup in its primary source—an ultraviolet-driven reaction between ozone and water. As a result, hydroxyl is less abundant now than when the industrial era began, some scientists suspect. Not that they have been able to measure the abundance of the fleeting molecule directly (see box). But their recent com-

puter modeling of the changing chemistry of the lowermost layer of the atmosphere, called the troposphere, suggests that since 1700 hydroxyl has decreased by perhaps 5% to 20%.

All is not lost, however. When the computer models that paint this discouraging picture are extended into the future, they offer a little encouragement—laden with a lot of irony. As even more pollutants accumulate, the models suggest, the atmosphere could shift into a new mode of operation that produces hydroxyl faster, bolstering the air's self-cleansing ability. But the boost in hydroxyl would come from some of the most noxious pollutants themselves—ones that are causing acid rain, destroying the ozone layer, and possibly warming the globe. Well-intentioned efforts to control these contaminants could condemn hydroxyl to a continuing decline, making the atmosphere even less able to cope with other pollutants. To scientists, the only clear lesson seems to be that halfway attempts to clean up the atmosphere will likely not be enough; the offending chemicals are too tightly linked in an intricate web of chemical and physical interactions.

The modelers who are bringing this mes-

Pinning Down a Will-o'-the-Wisp

For 20 years the hydroxyl radical has thumbed its nose at atmospheric chemists. The molecule, consisting of an oxygen bound to a hydrogen, is a pivotal player in the maze of chemical reactions that determines the composition of the lower atmosphere, but a practical means of measuring it has long eluded researchers. At a concentration of one hydroxyl for every 10 trillion air molecules, it is simply too scarce to be measured directly with sufficient speed and precision. But with theoretical models suggesting that this key atmospheric cleanser has suffered a worrisome decline (see main text), atmospheric chemists are more eager than ever to develop measuring devices.

Now several researchers think they have hydroxyl in their sights. The current leaders in the hydroxyl hunt are atmospheric chemists Fred L. Eisele and David Tanner of the Georgia Institute of Technology, who stumbled on a means of measuring it one summer day in 1987 as they were monitoring atmospheric ions near a high-voltage DC power line in Massachusetts. They were searching for ions produced by the power line, but they couldn't help noticing one species that was clearly responding to something else: the bisulfate ion, which peaked at midday and plummeted every time a cloud passed in front of the sun.

After a couple of days' thought, Eisele and Tanner realized what was happening. They knew that bisulfate ions are produced when hydroxyl radicals oxidize sulfur dioxide, a common pollutant. The rise and fall of bisulfate, they concluded, had to be tracking the rise and fall of hydroxyl as clouds and the passage of the sun altered the supply of

sage are quick to point out that their crystal balls are still too foggy to inspire great confidence. Anne Thompson of NASA's Goddard Space Flight Center in Greenbelt, Maryland, equates the current state-of-the-art in the modeling of tropospheric chemistry to that of stratospheric ozone modeling 10 or more years ago, when the alarm over the threat posed by chlorofluorocarbons (CFCs) had been sounded, but the projected ozone losses remained highly uncertain. Like the stratospheric modeling of yore, tropospheric modeling is plagued by uncertainties and oversimplification.

Thompson, for example, has built a one-dimensional model, which means that its version of the troposphere is just a single vertical line running from Earth's surface to the bottom of the stratosphere. The 25 interacting chemical species it traces can mix up and down along the line, but they can't circulate laterally, as in the real atmosphere. In an effort to compensate for this simplicity, Thompson has run the model separately for six regions distinguished by different latitudes, surface conditions (ocean or land), and pollution levels.

According to Thompson's set of simulations, the concentration of hydroxyl has decreased 23% globally since 1700. Much of the responsibility, according to the model, lies with two pollutants that consume hydroxyl: carbon monoxide from incomplete burning of fossil fuels and biomass, and methane from rice paddies, bovine digestive gases, landfills,

and natural gas leaks. Now other models—including two-dimensional simulations that depict the atmosphere as a north-south plane rather than a line and include up to 65 species—are supporting her result, showing hydroxyl declines of 5% to 20%.

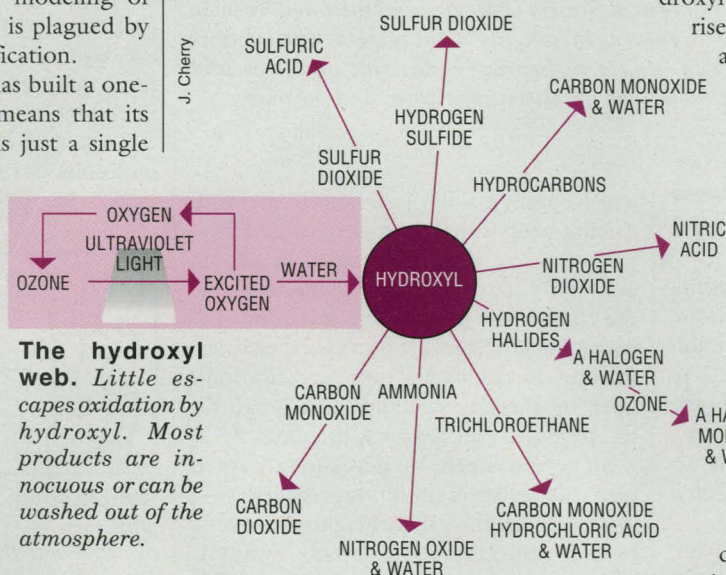
The consistency of the models in the face of all the uncertainties prompts Thompson to conclude that "hydroxyl has probably decreased with time." Many atmospheric chemists share that gut feeling, but some

the University of Oslo, for example, finds a minimal decline in hydroxyl over the next 10 years in his two-dimensional model. To be sure, the uncertainties that plague reconstructions of past trends only grow when models are extended into the future. One wild card: future pollutant trends, which could vary widely depending on economic conditions and regulatory steps. Still, other tropospheric-chemistry models behave much as Isaksen's does, predicting that hydroxyl concentrations will stabilize or even rise. And a common factor, assumed in

all the models, seems to be primarily responsible: a continuing increase in nitrogen oxides. These gases, generated mainly by the burning of fossil fuels, can regenerate hydroxyl after it oxidizes methane or carbon monoxide—reactions that ordinarily destroy the radical.

Nitrogen oxides aren't the only pollutant that could bring this paradoxical benefit. The expected rise in tropospheric ozone—the "bad" ozone that forms the eye-tearing, plant-destroying component of urban smog—would also boost hydroxyl abundance through its interaction with ultraviolet radiation. The continuing buildup of carbon dioxide, a greenhouse gas, could have the same beneficial effect: Along with the many social and environmental ills that a climate warming would bring, it would also increase atmospheric water vapor, another essential ingredient in hydroxyl production. And CFCs, by destroying the "good" ozone in the stratosphere and letting more ultraviolet light into the troposphere, could also speed hydroxyl formation even as they boost the skin cancer rate.

All these paradoxes amount to a cautionary tale for regulators. No matter which thread in the web of atmospheric chemistry they touch, it seems, the whole web trembles—a dilemma epitomized by the Montreal Protocol, which mandates that CFCs be eliminated to protect the stratospheric ozone shield. As the modelers have now shown, a renewed shield could mean less ultraviolet light reaching the troposphere and thus less of the hydroxyl needed to break down other pollutants—including the compounds meant to replace CFCs. And so regulators now have to wonder whether the currently planned CFC replacements would be innocuous enough for a world of scarce hydroxyls. "No matter what the regulation, there will be side effects," says Sze. The unavoidable challenge of restoring the web of chemical interactions will take a delicate hand. ■ RICHARD A. KERR



The hydroxyl web. Little escapes oxidation by hydroxyl. Most products are innocuous or can be washed out of the atmosphere.

ultraviolet light, which drives the reactions that generate the short-lived molecule.

Since those serendipitous observations, Eisele and Tanner have steadily improved on their technique. Instead of relying on the atmosphere's sulfur dioxide, they inject their own isotopically labeled sulfur dioxide, which the mass spectrometer can readily distinguish from background sources. Their system also includes chemical safeguards to ensure that they are measuring only atmospheric hydroxyl and not interfering substances or hydroxyl produced after the analysis begins. In just 5 minutes, the system can now detect as little as one hydroxyl molecule per 100 trillion air molecules—a sensitivity about five times better than that of earlier techniques. Eisele and Tanner think it should be good enough to test theories of hydroxyl chemistry directly.

Eisele and Tanner expect rivals in the field of hydroxyl measurement—indeed, they're looking forward to having them. "I'm not sure anyone is going to believe a single type of [hydroxyl] measurement," says Eisele. "Sometime there will have to be an intercomparison with other methods." The wait may not be long. After 16 years of development, atmospheric chemists Douglas Davis and John Bradshaw, colleagues of Eisele and Tanner at Georgia Tech, believe they are ready to construct their final version of an instrument based on a very different technique: laser-induced fluorescence of hydroxyl. If all goes well, the two Georgia groups could soon be going head to head in the hunt for hydroxyls.

■ R.A.K.