MIT'S MAGAZINE OF INNOVATION

TECHNOLOGY REVIEW

JULY•AUGUST 1998

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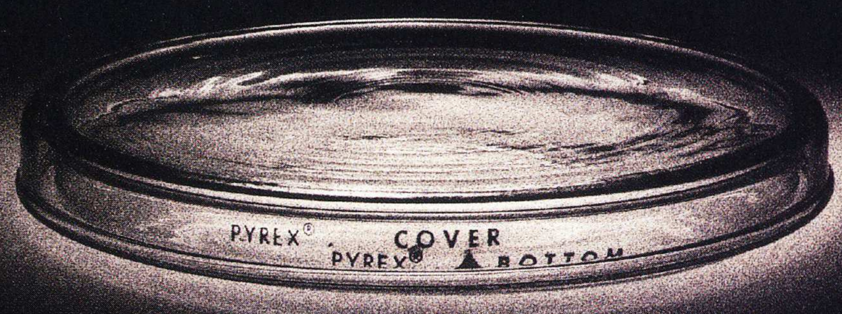
The biggest prize in biotechnology today is a cell that could be used to grow *any* type of human replacement tissue. But most companies won't even enter the race. Why not?



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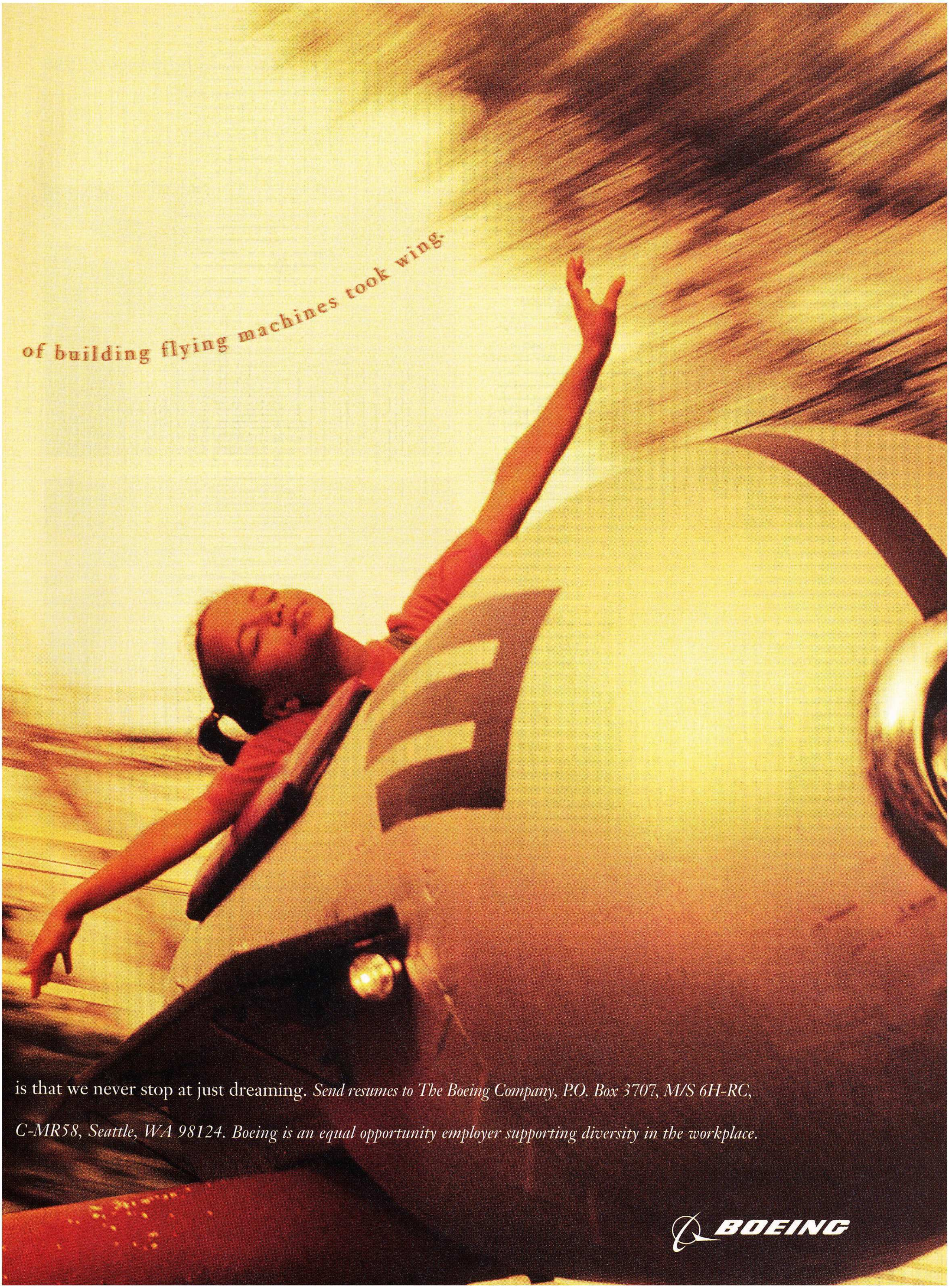
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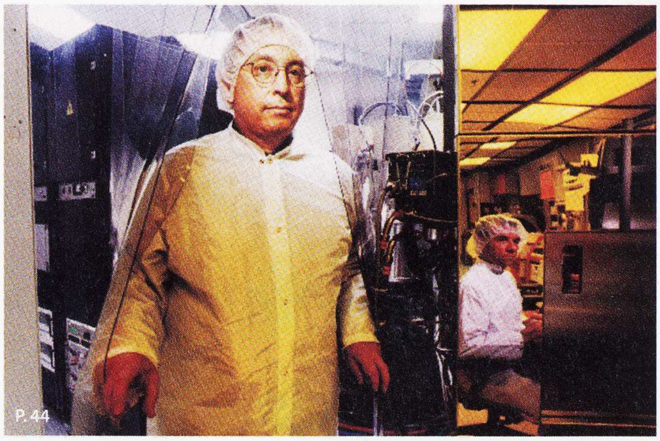

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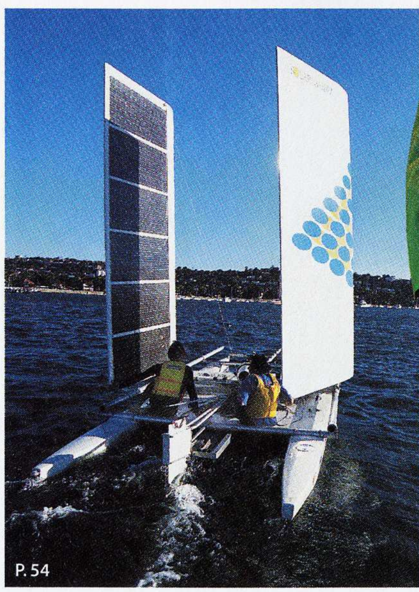

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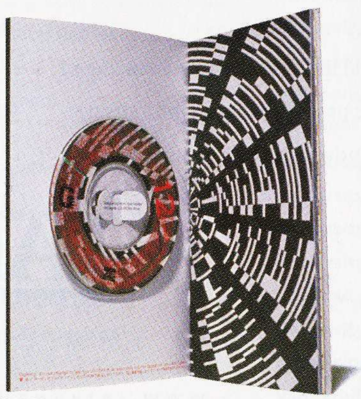

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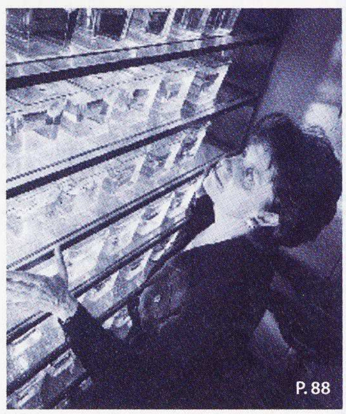

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PEOPLE

ORGANIZATIONS

Courage Needed

A MAGAZINE'S COVER STORY IS TYPICALLY NOT ONLY THE MOST COMPELLING ARTICLE in the issue but also the piece that best represents what the magazine is about. And our cover story in this issue—on the hunt for the human embryonic stem (ES) cell—offers a fine example of what the new *Technology Review* is all about. It combines cutting-edge research, a huge potential commercial payoff, important policy and ethical issues, and heated controversy.

Writer Antonio Regalado provides excellent reporting on an important area of biotechnology that has been given scant coverage by the major media. The cloning of Dolly the sheep last year elicited a tidal wave of attention; the announcement by John Gearhart of Johns Hopkins University that he had isolated human ES cells raised hardly a ripple. That's surprising, because the identification of human ES cells may have more impact on our species than Dolly ever will.

These remarkable cells are a *tabula rasa* for the human organism. Found in early-stage embryos, they are capable of differentiating into any other kind of human cell or tissue. If medical researchers could identify and reliably manipulate ES cells, it might open the door to being able to grow any kind of human replacement tissue—perhaps even whole organs such as new human hearts or livers.

But there are huge obstacles to that dramatic payoff. In addition to overcoming severe technical problems, researchers must negotiate thorny political and ethical dilemmas. That's because the biologists hunting for human ES cells use as starting material either fertilized human embryos left over from fertility clinics or human fetuses culled from abortions. These sources of tissue have led to threats against the researchers from some extreme members of the pro-life movement. The controversy has frightened away many researchers and most biotech companies.

Part of the problem is that the National Institutes of Health (NIH), which funds most basic biomedical research in the United States, has been prevented from getting involved in this area by a ban on federal funding for research involving human embryos. As a result, the only funding comes from the few biotech firms willing to take the risk. And when the only funding is private, researchers have a reduced incentive to publish their work (preferring instead to submit it directly to the Patent Office). What is more, their research doesn't get discussed at major scientific meetings; nor does it get the kind of ethical review that is given to publicly funded efforts such as the Human Genome Project.

The hunt for human ES cells must come out into the light. The ethical questions are too large for it to stay closeted and the potential payoff is too significant for the field to remain tiny and secretive. But bringing it out will require political courage from the White House, Congress and the NIH. The ban on research involving human embryos needs to be overturned, bringing federal funding to this area, along with the concomitant oversight. The stakes are too high for the hunt for human embryonic stem cells to remain behind closed doors.

—John Benditt

MIT'S MAGAZINE OF INNOVATION
TECHNOLOGY REVIEW

EDITOR IN CHIEF
John Benditt

SENIOR EDITORS
Herb Brody
David Rotman
Mary Tamer

ASSOCIATE EDITORS
Antonio Regalado
Abigail Mieko Vargus
Rebecca Zacks

CONTRIBUTING WRITER
Robert Buderi

EDITORIAL ASSISTANT
Deborah Kreuze

PRODUCTION MANAGER
Valerie V. Kiviat

COPY EDITOR
Troy Martin

ART DIRECTION
kellydesign
Kelly McMurray (AD), Margot Grisar

REDESIGN
David Herbick

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QUESTIONS: 617-253-8292, trsubscriptions@mit.edu.

ADDRESS CHANGES: General 815-724-1207, traddress@mit.edu; MIT Records 617-253-8270.

PERMISSIONS: 617-253-8292, trcomments@mit.edu.

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TECHNOLOGY REVIEW
201 Vassar St., W59-200
Cambridge, MA 02139
Tel: 617-253-8250
Fax: 617-258-8778
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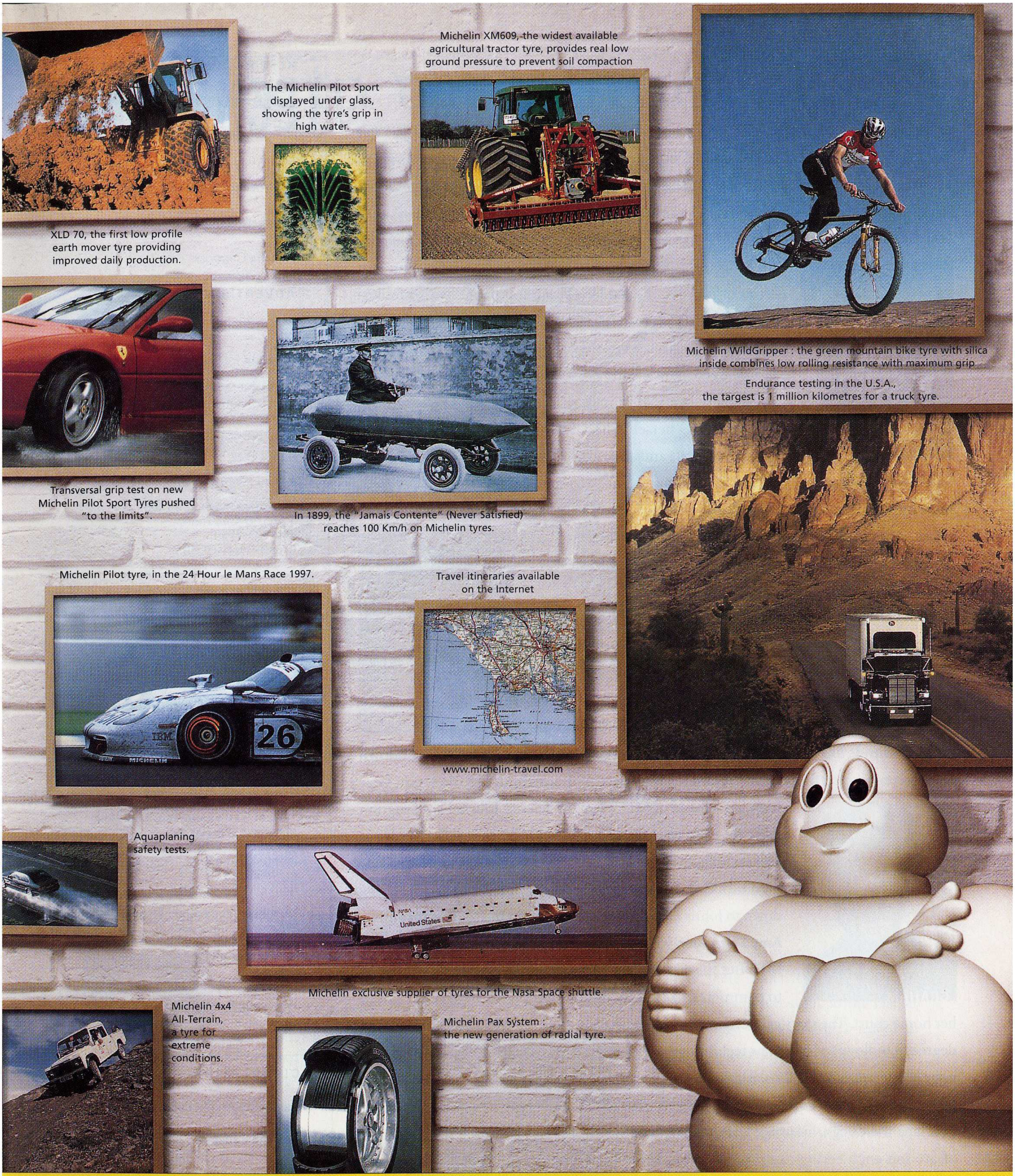


1898 - 1998 : Bibendum the Michelin Man celebrates 100 years of innovation.

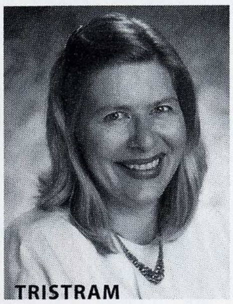
Michelin's aim has always been to make the world's best tyre. Take a look at our track record : the revolutionary radial concept, space shuttle tyres, low profile ultra high performance Michelin Pilot Sport, giant earthmover tyres weighing more than four tonnes, to mention but a few. We are constantly at our innovative best to help everyone get around more easily. While the world is on the move, you can be sure that Bibendum the Michelin Man will be with you on all terrains and in all weather conditions.

1998 BIBENDUM

MICHELIN

Plus nous progressons, mieux vous avancez.

Our cover story is the second feature by one of the new members of the *TR* staff. In "The Troubled Hunt for the Ultimate Cell," Associate Editor **Antonio Regalado** uses his insider's view of biotechnology to get to the heart of a field that could alter the face of medicine. The band of researchers that he's profiled—who are hunting for something called "the human embryonic stem cell"—are buffeted by threats of violence, political controversy and funding bans. | This month, we continue our series of profiles of great labs at big companies with a look at IBM's Almaden Research Center. **Claire Tristram** explains how Almaden's research scientists have kept themselves relevant in the era of corporate cutbacks by repeatedly breaking the storage density barrier for magnetic disk drives. Tristram is no underachiever herself. She's a book author, a black belt who speaks Japanese and a motorcycle enthusiast. After a career in technology marketing, Tristram turned to freelance journalism in 1995, quickly building a mountain of bylines at magazines such as *Fast Company* and *Wired*. | Bringing us a tale of innovation from Down Under is **Dan Drollette,** an American exploring Australia on a Fulbright traveling fellowship. In "Solar Sailor" he describes a sun-worshipping waterbug he discovered at the Second International Advanced Technology Boat Race in Canberra. Drollette has also written on the aerodynamics of aboriginal boomerangs and about snorkeling with 15-meter-long whale sharks for publications such as *The Sciences* and *Australian Geographic*. | Mining asteroids for minerals? It sounds like science fiction, but seasoned reporter **David Graham** tracked down an entrepreneur setting out to commercialize space with low-budget rocketcraft. Graham, a graduate of MIT's Knight Science Journalism program and a frequent contributor to *TR*, covers science at the *San Diego Union-Tribune*. If this first venture into the void succeeds, Graham thinks that big aerospace firms could be next. | Trekking down to Johns Hopkins was a break from the routine for author **Amy Salzhauer,** who is earning a PhD in Technology Policy at MIT. But the tale she tells of two materials scientists struggling to commercialize a thin, lightweight plastic battery is right in her home court. The story calls on her understanding (she holds an MBA and an advanced degree in biology) of how new technology wends its way into the private sector. | In this issue's "Viewpoint," MIT Assistant Professor of Design and Computation **John Maeda** presents a critique of computer art. Thanks to training in both computer science and classical Japanese design, his images are graphic proof that the union of art and engineering can produce remarkable work that is beyond the reach of either discipline individually. | We Must Have Heard Voices: In our excitement at getting out the first issue of the "new" *TR*, we managed to misstate the title of Contributing Writer Robert Buderi's book on radar. Bob's book is *The Invention that Changed the World,* published by Simon & Schuster.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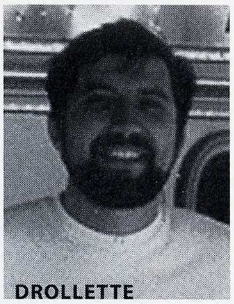
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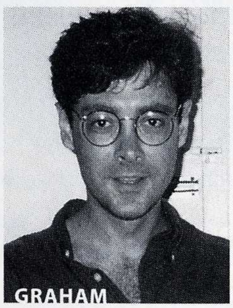
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MIT'S MAGAZINE OF INNOVATION
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PUBLISHER AND CHIEF EXECUTIVE OFFICER
R. Bruce Journey

ASSISTANT TO THE PUBLISHER/CEO
Elizabeth Surano

ASSOCIATE PUBLISHER
Martha Connors

ADVERTISING

DIRECTOR OF ADVERTISING SALES
Paul Gillespie

ADVERTISING SALES ASSISTANT
Amanda J. Prugh

NEW ENGLAND/BOSTON: Paul Gillespie
617-253-8229
pgillespie@mit.edu

MID-ATLANTIC/NEW YORK: Yvonne Cooke
Karen Gleason and Associates
212-213-6770
y_cooke@.msn.com

SOUTHEAST/ATLANTA: Tim Reis
T. Reis & Co., Inc.
770-993-7730
timreis@treisco.com

SOUTHWEST/DALLAS: Phil Ganz
The Ganz Company
972-991-4994
philganz@ganzcompany.com

MICHIGAN/DETROIT: Mary Luongo
Kathleen G. Charla Associates
248-816-9800
mluongo@detroitsales.com

MIDWEST/CHICAGO: Karen Gleason
Karen Gleason and Associates
312-993-4111
Mike Barr
Lisa Nelson
moneymal@enteract.com

NORTHWEST/SAN FRANCISCO: Gigi Volk
Magazine Services inc.
gvolk@msi-sf.com
Jennifer Purcell,
415-356-7591
jpurcell@msi-sf.com

SOUTHERN CALIFORNIA/LA: Gregory Schipper
White Associates, Inc.
310-451-5655
gschipper@aol.com

EUROPE: Anthony Fitzgerald,
David Wright
Media Media Ltd.
44-171-630-0978
afitzgerald@enterprise.net

CIRCULATION

CIRCULATION PROMOTIONS MANAGER
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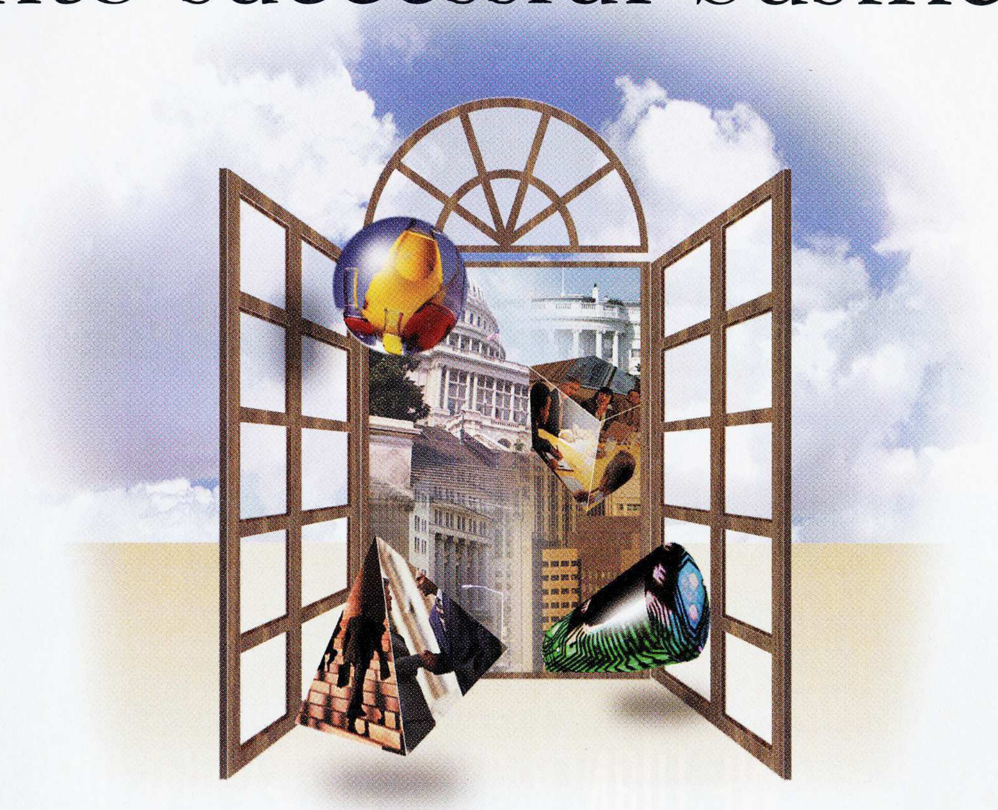
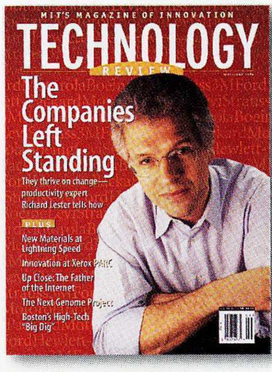



WE TURNED A CENTURIES OLD IDEA
INTO A TWENTY-FIRST CENTURY INNOVATION.

> "*I regard* Wired *and* Fast Company *as the best technology magazines, and now* Technology Review *is on a par with them.*"

Readers Review the New *TR*

CONGRATULATIONS ON THE NEW INCARNATION of *Technology Review!* I had become bored with the magazine, and had been thinking of letting my subscription lapse. Your makeover has revitalized the publication and recaptured my interest. I like what you've done across the board—the new orientation of the articles, the new layout and typography—even the new paper. I regard *Wired* and *Fast Company* as the best technology magazines, and now *Technology Review* is on par with them.



DEREK SCHULTZ
President, Media Design Associates
Randolph, NJ

BY CHANGING *TECHNOLOGY REVIEW* FROM a highly respected source of broad technical opinion to a high-tech business journal, you have made it easier for this old curmudgeon to winnow his awesome stack of reading material, a continuing task in this age of informational glut. What was formerly a "must read" has become a "glance and discard."

WILLIAM E. MOORE II
Charleston, WV

I'VE JUST FINISHED BROWSING WHAT I understand is your first issue of the new *Technology Review* and I wanted to let you know that it is fantastic. Being an avid reader of both *Fortune* and *Scientific American*, I feel that you have managed to capture the essence of both in what is promising to be an interesting, informative and insightful business-technology journal.

IDDO GILON
Cambridge, MA

PLEASE DON'T TURN *TR* INTO A COMPANY claque. Corporations praise themselves, regularly and without embarrassment; you needn't do it for them. It is the *ideas* "left standing" that interest most of us—not the wit and wisdom of top management.

E. COHEN
Chicago, IL

IT IS GREAT! THE LAYOUT IS easy and the content appears to be expanded. The lead on companies that have survived is one of the best I've read. I was very satisfied with the old version, but the new is even better.

PETER D. NUGENT
Via the Internet

I HOPE WHAT I RECEIVED today represents phase one of a "new Coke" gambit—the substitution of a new and inferior product for one that had commanded strong, but unexpressed, loyalty. With that strategy, outcries and widely publicized protestations of love for the original product will be followed by its reintroduction to an energized market. Please don't delay in bringing us Classic *Technology Review.*

WILLIAM A. SELKE
Stockbridge, MA

I JUST RECEIVED MY MAY-JUNE COPY OF *Technology Review.* It is great. The magazine is filled with more articles and overall looks better than in the past. Now hopefully the magazine will come monthly instead of bimonthly, even if you have to raise the subscription price.

BILL KNOTT
Via the Internet

We welcome letters to the editor.

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E-mail: technology-review-letters@mit.edu.
Please include your address, telephone number, and e-mail address.
Letters may be edited for clarity and length.

I COMMEND THE "NEW" *TECHNOLOGY Review.* The departments, features, "back of the book," and columnists come through as Editor in Chief John Benditt confidently projects in the Leading Edge. I stopped to read rather than skim *TR.*

EUGENE N. BILENKER
Elizabeth, NJ

YOUR CRASS ENTREPRENEURIAL CHEERleading leaves me cold. It is becoming ubiquitous nationally as our economy becomes more steeply and structurally stratified, with a concurrent loss of political and economic influence by those classes of people unable to hop on the high-stakes, high-tech bus.

You have abandoned *Technology Review's* commitment to the advancement of technology for the betterment of mankind as a whole. While your narrower focus on the business implications of technology may make it easier to sell advertising space, it abandons even a pretense of the objectivity and moral high ground that were the trademarks of the earlier *Technology Review.*

DON COOLIDGE
Belmont, CA

I HAD ALWAYS LOOKED AT *TR* AS A BIT stodgy, with maybe one or two interesting articles per issue. I am impressed by the new focus and format, and am especially encouraged by the increased coverage of biotechnology so evident in the May/June issue. I found virtually all the articles of great interest. I'm proud of my alma mater's continuing ability to innovate.

JOHN GREENE
Gaithersburg, MD

I'M NEVER VERY PLEASED WITH CHANGE, and had grown pretty used to the non-commercial and pretty low-key approach of the old *TR.* My enthusiasm was high for the "niche" magazine, and I'm not at all sure I'll stay on with the much more mainstream product it's just become. But my subscription has a couple of years to run, and I'm open to the possibility that the new publication will grow on me.

EDWARD RICE
Vienna, VA

SORRY, BUT I THINK YOU OVERDID THE innovation angle in your new format. However, on the positive side, as one of the myriad of engineers and technicians who installed the high-speed data lines between universities in the 1960s, I did enjoy the Vint Cerf interview.

BILL BURESCH
Via the Internet

JUST A QUICK NOTE TO COMPLIMENT YOU and your staff for a great "new" *Technology Review.* One of the first things I'll look to in future issues is Trailing Edge—that's a cool page.

TOM HULL
Myrtle Creek, OR

BEST WISHES ON REVAMPING *TECHNOLOGY REVIEW.* As president of a small technology-based company, I have always felt I should be a subscriber. In fact, I have subscribed three times over a period of 15 years. Each time I have either cancelled or tossed them in the trash because reading them always made me angry. The primary reason was that I resented a scientific publication from a prestigious institution being subverted to a political end. Scientists have a moral obligation to address issues of public well-being and information. They also have an obligation not to promote a political agenda under the mantle of being a scientist or an affiliation with a scientific institution.

JAMES P. LEWIS
Spring, TX

THE OLD *TECHNOLOGY REVIEW* PLAYED AN important role for many of us who, while not ready to buy Ted Kaczynski's manifesto, still regard the impact of technology with a jaundiced eye. The old magazine was one of the few places where I could find a literate, informed and balanced critique of untrammeled enthusiasm for technology as the solution to all our problems. And there were special gems, like the article from the July 1989 issue on James Lovelock's "Gaia Hypothesis."

In the May/June issue, on the other hand, I read enthusiastic praises of the "Winning Combination" of combinatorial chemistry, the "real payoff" from the next genome project, and how MIT's guru of productivity calls for a "New Economic Citizenship...based on how America's most successful corporations navigate turbulent economic conditions."

RUSSELL BRADNER NORRIS, JR.
New Rochelle, NY

LAST THURSDAY, I RETURNED FROM SEVERAL weeks traveling and discovered the new *Technology Review* in my mail. For the first time in many years, I plan to read the entire issue. Congratulations. Excellent content, well-written and exciting graphics. Well done.

FRANK ZENIE
Via the Internet

I HAVE BEEN A SUBSCRIBER TO *TECHNOLOGY REVIEW* for perhaps 15 years. While I have enjoyed it, I do believe the time was right for a reorientation of *TR* and what it could accomplish. I am not an engineer or in a technical field. However, I am in the group among which I believe you want to expand readership: sophisticated lay people who know they must stay apprised of technology and innovation issues. I will wait for a few issues before commenting on the content, but I do want to communicate my reaction to the "new look." In general it is a much more updated look, good font choices, good graphics. What I don't understand is the excessive, distracting underlining of headlines, featured comments, etc.

MONICA MANNING
St. Paul, MN

YOUR NEW FORMAT IS A DISASTER. THE TYPE face is too small, and the sidebars printed on a colored background are illegible. No, I am not turning senile or going blind. I am still working under contract with a major national laboratory doing technical editing (including formatting).

MARGARET DIENES
Las Vegas, NV

I WANT YOU TO KNOW HOW IMPRESSED I am with *Technology Review*'s new look. It is clean and modern and easy to read. I began my subscription about a year and a half ago and have enjoyed the content tremendously. The new look (and new paper) adds an extra bonus. Congratulations!

KATHY WILLIAMS
Via the Internet

YOUR EXPERIMENT WITH INNOVATION IS commendable. It is obvious a lot of work has gone into the new format. Unfortunately, the innovation went in the wrong direction. The cover is no longer unique—I could not pick it out in my unisex barbershop from *US, People, Teens* and all the other splashy magazines. Inside the magazine, it looks like a novice just bought a desktop publishing program. It's difficult to tell the articles from the advertising.

JACK L. SHELTON
Littleton, CO

WOW! WHAT A GREAT NEW LOOK FOR YOUR magazine. It's bright and engaging. The photos are much more dramatic and compelling than they used to be. The color and type says you're wired into the present. I love it.

LEE GIGUERE
Willington, CT

Pore Pioneers

YOUR REPORT ON A NEW TECHNIQUE FOR DNA sequencing ("Hole in Wall Offers Cheaper Sequencing," *TR May/June 1998, page 26)* did not properly assign credit for this landmark work. In particular, the article ignores the contribution of the National Institute of Standards and Technology (NIST), which did the pioneering work showing that individual polynucleotides can traverse a single nanometer-scale pore. The work described in your article is a collaborative effort between John Kasianowicz of NIST, Daniel Branton of Harvard and David Deamer and Mark Akeson of the University of California at Santa Cruz. Moreover, the article says that research results provide proof of concept that this method will be successful for sequencing individual nucleotides. NIST researchers feel it is premature to draw this conclusion.

LINDA JOY
Public Affairs Specialist, NIST
Gaithersburg, MD

Science Journalism Defended

I CAN'T AGREE WITH GARY TAUBES' NOTION that science and daily journalism are so "fundamentally at odds" in purpose that they cannot find common ground ("Telling Time by the Second Hand," *TR May/June 1998, page 76)*. He notes that scientific knowledge progresses by "fits and starts." Why isn't this equally acceptable in the news?

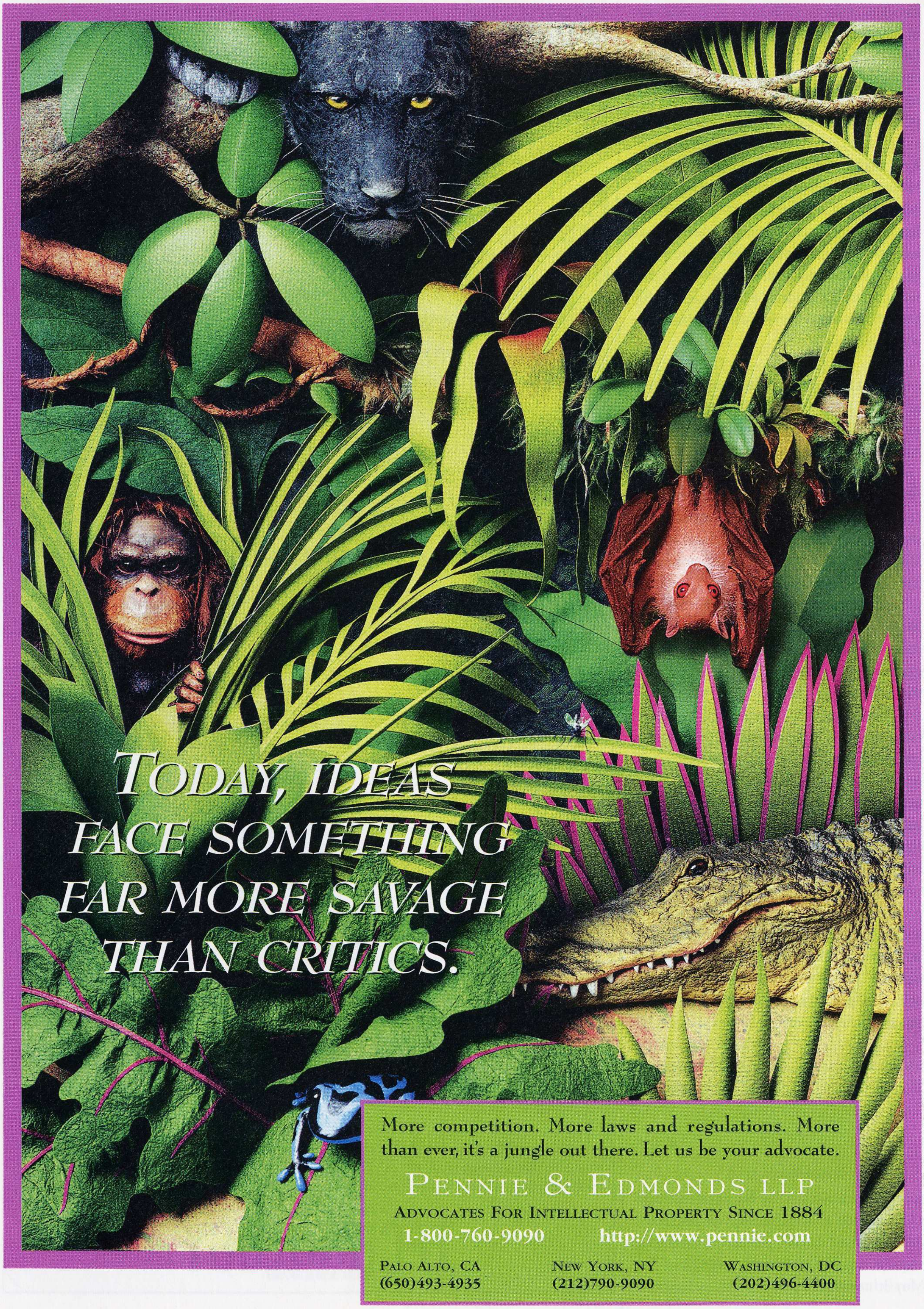
He suggests that journalists should be wary even of published findings and rely more on "real experts" to assess any scientific claim. But who will select these experts? If scientific peer review is inadequate protection against false or hyped claims, why expect journalists to construct a better filter?

Like science, daily science reporting proceeds haltingly, struggling toward a more accurate picture with every new story and new piece of information. If we truly want the public to understand science, we need to report it not as a finished product but as a work in progress.

TOM PAULSON
Seattle Post-Intelligencer
Seattle, WA

CORRECTION

John Kasianowicz of the National Institute of Standards and Technology should have been credited as the source for the DNA sequencing illustration on page 26 of the May/June issue.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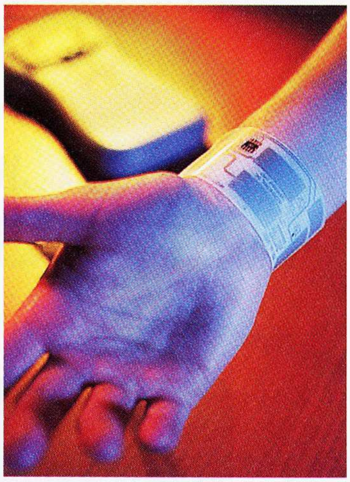
A Flip of the Wrist

Whether you push a broom or type on a keyboard, you're at risk for carpal tunnel syndrome (CTS). But, unless you're a neurological specialist, this damage to nerves in the wrist is tough to diagnose. "Lots of things look like CTS, including arthritis, wrist sprains and hypochondria," says bioengineer Shai Gozani.

Gozani's company, NeuroMetrix of Cambridge, Mass., has designed a flexible Mylar strip embedded with electrical sensors, circuits and a tiny processor that should enable the family physician to identify CTS. Positioned at the heel of the wrist, it shoots a current through the nerve, causing thumb muscles to contract and produce impulses of their own. The sensors pick these up, allowing the processor to calculate the speed of the nerve signals. Normal nerves carry signals at about 60 meters per second, but damage by CTS can slow that by half.



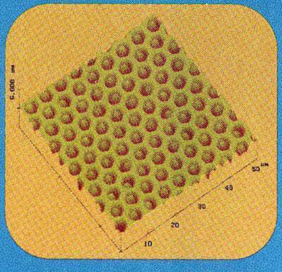
VITO ALUIA

Sensors check for damaged nerves.

Lab-on-a-Tip

A fiber-optic cable is a bundle of thousands of light-carrying glass threads. A start-up called Illumina in San Diego plans to put a test tube on the tip of each.

Born in the Tufts laboratory of chemist David Walt, the scheme uses hydrofluoric acid to etch a dimple at the end of each fiber. The teensy wells—each holds just a billionth of a microliter—can be filled with reagent-bearing beads or cells. Expose the bundle end to a patient's blood or to a test chemical that induces a light-generating reaction and each test tube sends in a report via its fiber. Illumina is betting that the lab-on-a-tip will speed diagnostic tests, chemical sensing and genome experiments.



An array of puny petri dishes.

Tiny and Tunable

The telecommunications industry has big plans to dramatically increase information-carrying capacity by using multiple colors of light in an optical fiber. Great idea, but its practicality depends on a laser that can be "tuned" to different wavelengths. Constance Chang-Hasnain, professor of electrical engineering at the University of California at Berkeley, may have an answer.

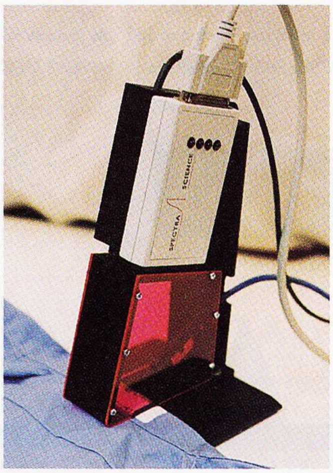
A laser's color can be changed by resizing its "resonant cavity"—the space in which photons bounce back and forth before emerging as a beam. In Chang-Hasnain's device, a small increase in voltage causes a tiny cantilever arm to lower a mirror toward the chip—shrinking the resonant cavity and shortening the wavelength. The device can now be tuned across wavelengths spanning about 30 nanometers. Chang-Hasnain aims to triple that, making possible hundreds of separate communications channels.

Bone Phone

DAEWOO TECHNOLOGIES

Most devices designed to help the hard-of-hearing simply amplify sound. This approach doesn't work well for people with severe defects in the outer or middle ear. Daewoo Technologies of Lyndhurst, N.J. has developed a telephone that takes a different approach: sending vibrations directly to the inner ear through the bones in the head.

We hear mostly by "air conduction," with sounds traveling through the ear canal and middle ear to the inner ear, where they are translated into nerve impulses that go to the brain. But we also hear via "bone conduction," and Daewoo's phone exploits this effect. A knob in the center of the earpiece is pressed to a bony part of the head and transmits vibrations directly to the inner ear. The phone's makers say the instrument could also be useful for people with normal hearing who work in noisy environments such as construction sites.



SPECTRA SCIENCE

New thread makes smarter fabric.

Laser Linen Tag

Add up all the restaurant tablecloths, hospital bedsheets and work uniforms that people use every day, and you get a linen industry that has to track billions of items. New materials developed by Brown University physicist Nabil Lawandy may streamline this task.

The materials return specific frequencies of light when struck by a laser beam. Putting an array of threads spun from this material into the border of a tablecloth or the label of a garment results in a "smart textile" that identifies itself optically under laser illumination. The threads are faster to read and more durable than the bar codes and radio chips now used for identification. Spectra Science of Providence, R.I., has formed a textile-manufacturing division called Millennium Textiles to commercialize the new material.

Time for Fresh Air!

In the dim past, if you wanted to place a long-distance phone call, you booked ahead of time and the connection was made by an operator, but if you wanted to make a local call, you dialed direct. These different ways to reach your party sound crazy today. Yet that's exactly what we do with computers: We use an operating system like Microsoft Windows to work with local information in our own machines while relying on a different system—a browser like Netscape Communicator—to deal with long-distance information in other machines around the world. There's no reason for this craziness, other than the historic emergence of browsers 40 years after operating systems. It's time for a change!

By now, developers have realized this and have begun combining operating system software and browser software, mostly by adding the features of one to the features of the other. This will result in a tangle of commands and conventions, covered by a thin cosmetic user interface veneer...to make us feel good. No such veneer, however, can hide the underlying differences of dealing with information: For example, in a browser, clicking on an icon opens a distant home page, but in an operating system clicking on an icon selects it for further action. Retaining both capabilities is as sound as turning the steering wheel to steer the car when driving in your neighborhood streets and turning the steering wheel in the same direction to apply the brakes when driving in the country! Besides, there are some actions you can do with an operating system on local information that you cannot do on distant information with a browser—and vice versa. Yet system developers are accumulating the features of browsers and operating systems to conserve financial and emotional investments in both breeds of software. The result is still unfit for human use.

The time has come for a new metaphor, as fresh as the air we breathe, that will replace stale operating systems, browsers and awkward combinations of the two. Much like today's direct-dial telephone, a single new system would let us deal more economically, more naturally and more uniformly with information, wherever it may reside.

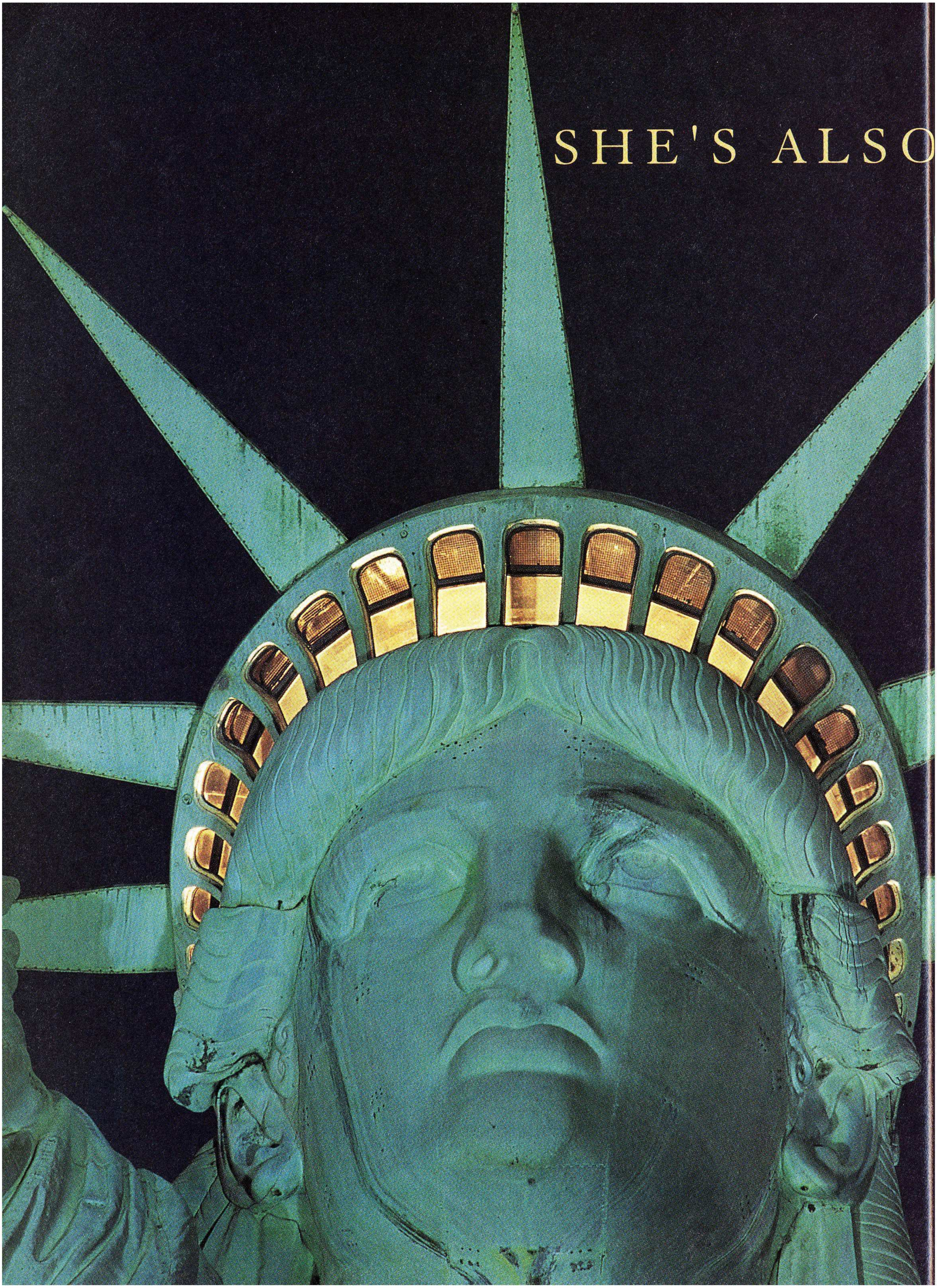
Whether they use operating systems or browsers, people want to do the same relatively few things with information—navigate through it to find what they seek, transfer it to or from other places, build on it with new information they acquire or generate themselves, feed it to a program or apply it as a program to other information, and perceive it with their eyeballs and ears. And they want the assurance that their information will not be used by others without permission. Interestingly, what people do with information closer to their specialties is not very different from these more elementary operations. Doctors navigate through patient records, build on the information there, transfer it to insurers and specialists, supply it to charting and analysis programs and display it or print it for their use. The right new metaphor should carry through, all the way up to applications.

To many technologists, the metaphor I am calling for is viewed as lower-priority "user interface" stuff. Underneath such "niceties" for the user, they see big differences between computers on which operating systems act and the networks on which browsers act, with different techniques needed for these two environments. These differences in mechanism are indeed there, as they are in today's telephone

Stale browsers and operating systems must be replaced with a new system that allows users to work uniformly with data in their own computers—or around the world.

systems: Copper twisted wires link your house and office to the local phone exchange while glass fibers link exchanges together across long distances, with different mechanisms used for routing and amplifying voice signals in the local and remote telephone networks. But users of the telephone are oblivious to these differences. To them, the telephone system helps them reach people uniformly. Period! It's high time we technologists learn this lesson and shed our system-centric preoccupation that has governed our designs for decades: Let's stop throwing our system and subsystem intricacies on users. Let's, instead, use our ample technological arsenal and creativity to give users the simplest, most useful people-oriented systems we can create that address their needs.

Coming up with a new fresh-air metaphor for dealing uniformly with local and distant information, instead of a bloated conglomeration of current operating system and browser commands, would be a very big step in this direction. It would also be as historically significant as the 20-year transition from a DOS-like world where the computer drove humans with multiple choice questions, to the desktop world of WIMP (Windows, Icons, Menus, Pointing) pioneered by Xerox PARC, then Apple and Microsoft. The benefits to people would be the ease of use we keep harping on, the human power to do more useful things by blending distant and local information, and the emergence of faster systems, freed at last from layers and layers of stale software. Let's open the windows and allow the fresh air in! ◊

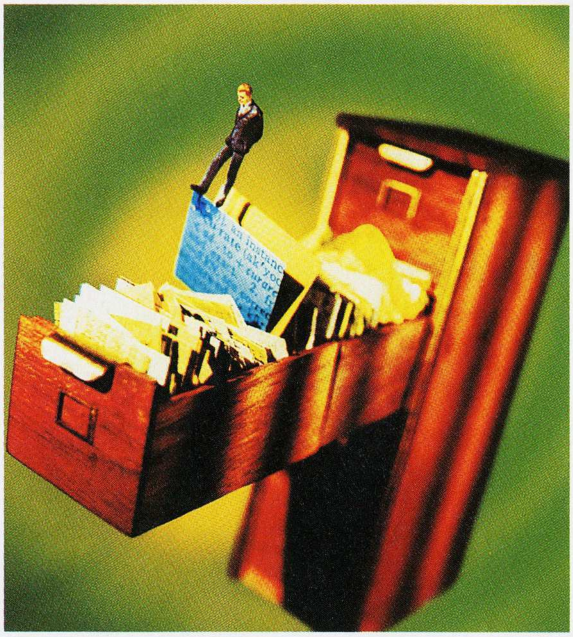

SHE'S ALSO

BENCHMARKS

INFOTECH

Untangling Web Searches

A more discerning way to find information


STEPHEN WEBSTER

WEB SEARCHES OFTEN EVOKE A TWO-part reaction. First: Wow, that was fast! Followed sadly by: But none of this is what I want. Lightning-quick online searches typically lead Web users into piles of documents that are, to be kind, of dubious reliability. Unlike the carefully catalogued stacks in a library, the Web often appears to be untouched by human judgment.

This chaos has been the price Web users pay for an open system to which anyone can contribute. But it is an unnecessary price, says Jon M. Kleinberg, a professor of computer science at Cornell University. Kleinberg has devised an approach for sifting the contents of the Web that could go a long way toward solving what he calls the Web's "abundance problem."

Kleinberg's technique relies on the premise that despite the jumbled appearance of the Web, critical thinking is in fact woven throughout it. Every time a page's creator includes a link to another site, that is a vote of confidence in the linked-to page. Thus a rough measure of a site's value can be derived by counting how many other sites are linked to it. "The Web is explicitly annotated with precisely the type of human judgment that we need in order to formulate a notion of authority," says Kleinberg.

But this measure needs to be refined, because if it were used alone, the Yahoo search directory and the Netscape homepage would come out near the top every time. "We need a way to throw those pages out," Kleinberg explains. The solution? Kleinberg applies a second level of filtering that assigns higher value to pages that include lots of links to other sites that are themselves relevant to the search.

By viewing the Web through its linkages and not merely by key words, Kleinberg's search algorithm solves another common search problem. A conventional Web search on the word "jaguar," for example, generates an unsorted roster of sites—most related to the sports car or to an obsolete computer with the same name. Information on the jungle cat that inspired these brands, however, is harder to come by. Kleinberg's system automatically groups hit lists into "communities" of sites that reference one another, in this case providing a list subdivided by those related to cars, computers and cats.

Kleinberg developed the algorithm while at IBM's Almaden Research Center in San Jose, Calif., which still owns it. For now, the enhanced searching tool remains experimental, but IBM researchers are shopping it around to companies that run online search services, including Alta Vista operator Digital Equipment Corp. Widespread availability is "inevitable," says Prabhakar Raghavah, manager of computer science principles at IBM Almaden. "This is a great idea whose time will surely come."

— Herb Brody

POLICY

United States Slips in the Materials World

The United States has long been regarded as the international top gun in materials science. But the post-cold war shrinkage of U.S. military spending—and the resulting loss of the Defense Department's generous support for materials research—is rapidly changing the balance of power.

A recent report by the National Academies of Sciences and Engineering and the Institute of Medicine says the United States remains among the leaders in most areas of materials science, but for some key materials, including composites, catalysts, polymers and biomaterials, its leadership is eroding. The report, called "International Benchmarking of U.S. Materials Science and Engineering Research," found that the United States is particularly weak in synthesis and processing research, and that some of its major research facilities are underfunded and outdated. Arden L. Bement, professor of materials and electrical engineering at Purdue University and chair of the panel, says, "A lot of other countries are beginning to challenge in some very critical areas."

—David Rotman

BIOMATERIALS

New Starring Roles for Collagen?

Structural insights could expand uses

Animals are cut from a cloth woven largely of collagen. This rope-like protein is the most abundant in the body, giving structure to tissues such as skin and cartilage, but to date chemists haven't fully understood the source of collagen's strength. A prevailing theory dictated that the molecule—a tightly wound triple helix—was braced by a scaffolding of water molecules. But research from the University of Wisconsin-Madison points to a different answer, one that not only helps explain collagen's properties, but also might eventually expand the protein's utility in cosmetic surgery, wound healing and perhaps even arthritis diagnosis and treatment.

Wisconsin biochemist Ronald Raines and his co-workers modified collagen so that it was incapable of forming the "water bridge" bonds previously thought to help hold the molecule together. The new form is able to endure temperatures more than 22 C higher than a model of natural collagen, probably because added fluorine atoms push the chains into a sturdy configuration, the researchers explain in the April issue of *Nature.*

Natural collagen is already a useful biomaterial, most famous for its starring role in


THE KOBAL COLLECTION

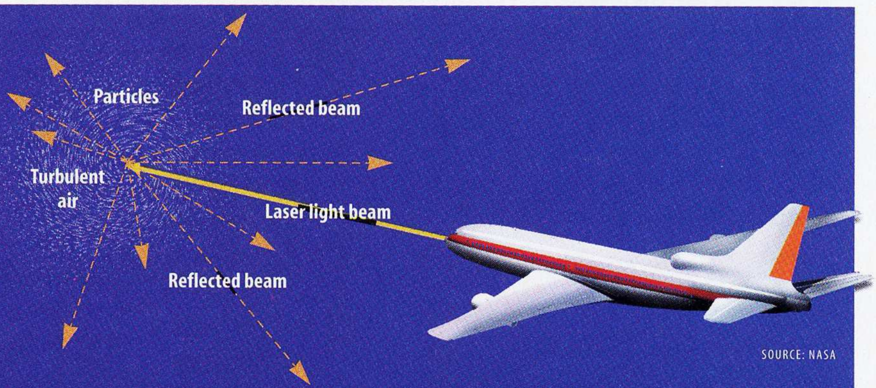
the full lips and wrinkle-free faces of movie stars and models. But the protein tends to unravel in the body, so collagen injection must be repeated every few months. Raines believes that a more stable artificial collagen could be an advantage not only in plastic surgery but also in artificial tissues, organs and perhaps even in a protein "solder" that could be melted into wounds for sutureless healing.

MIT polymer engineer Ioannis Yannas says that the Wisconsin work is an important advance in understanding the structure of collagen. He cautions, however, that the findings don't guarantee practical uses for artificial collagen. For one thing, the molecule must prove to be nontoxic. And there is a "big gap," Yannas says, between knowing the chemical structure and developing a new biomaterial.

Brian Butcher—vice president for research at the Arthritis Foundation, which helped fund Raines' research—says that the new insight into collagen "could have very important repercussions" for arthritis. The joint ailment is often the result of collagen-rich cartilage breaking down; Butcher sees the potential to develop better tools for detecting the destruction. In time, Butcher says, researchers might even learn how to replace or strengthen collagen structures in arthritic joints, reweaving the worn tissues with stronger stuff. **—Rebecca Zacks**

TRANSPORTATION

Avoiding the Rough Spots



SOURCE: NASA

Although today's commercial aircraft are more than tough enough to withstand being bounced about by air pockets, sometimes passengers aren't: Turbulence in otherwise calm stretches of air is the leading cause of in-flight injuries. Seeing turbulence ahead of time could save airlines millions of dollars a year, by averting in-flight injuries and also by saving fuel wasted in churning through bumpy air. The National Aeronautics and Space Administration (NASA) is testing a sensor device that could do just that.

The device, designed and built for NASA by Coherent Technologies of Lafayette, Colo., uses LiDAR technology. LiDAR is the optical analog of radar: Instead of radio waves, pulses of infrared light are transmitted, some of which bounce off particles and back to a sensor. NASA's sensor detects the changing velocities of tiny particles in turbulent air, creating a picture of the rough air ahead.

The sensor now only "sees" straight ahead. But the goal is to be able to scan horizontally and vertically to get a three-dimensional picture of the turbulence. At this point, the laser-based sensor can see approximately four miles ahead, which for a commercial jet translates to a warning time of 10 to 30 seconds.

"They'd like five minutes," says Rod Bogue, project manager at NASA's Dryden Flight Research Center in Edwards, Calif. "But 10 to 30 seconds is better than nothing." Just ask anybody who's been through turbulence lately. **—Deborah Kreuze**

BETSY HAYES

Pioneer Hi-Bred's insect-resistant, transgenic corn.

PIONEER HI-BRED INTERNATIONAL

BIOTECH

Plant Startups Find Fertile Ground

Gene hunters test their skills on crops

HIGH-TECH INVESTORS HAVE LONG CONsidered agriculture to be a losing proposition, scorning it as a backwater in favor of fast-growing biotech sectors focused on human health. But the budding success of the first generation of genetically engineered crops—and projections that growth will skyrocket over the next several years—is rapidly catching the attention of entrepreneurs and venture capitalists.

In the latest example, Burrill & Co., a San Francisco investment house, is raising a $100 million war chest earmarked for new agriculture startups. "This is a huge amount of money for ag biotech. There hasn't been much money going into this sector at all," says Roger Wyse, the former dean of the University of Wisconsin's College of Agriculture and Life Sciences, who is directing Burrill's investments. Backed by such corporate giants as Bayer and Hoechst, the managers of the fund see plenty of opportunity in this underfunded field.

The reason for all the interest is clear. Big agricultural chemical producers like Monsanto and DuPont and seed suppliers like Pioneer Hi-Bred International have looked into their farmers' almanacs and concluded that biotech is the future. The ag giants are already selling seeds for herbicide-resistant soybeans and insect-fighting corn. First commercialized several years ago, these genetically engineered crops are proving to be blockbusters. And the projected growth numbers are staggering. Analysts predict that biotech crops will be worth $7 billion by 2005.

Companies are now looking for the next batch of genes to further engineer crops. Research groups are busily developing biotech plants that will be designed with "output" traits to, say, pack in more protein or more starch. A third wave of biotech crops is on the drawing board that will be engineered to produce nutritional supplements or raw materials for industrial processes.

But fulfilling such dreams is going to take extensive knowledge of plant genes. Which is where the startups hope to come in. The sudden influx of venture capital and the promise of more to come is fueling a slew of new plant biotech companies *(see table)*.

A number of the startups are borrowing well-tested genomics techniques (methods for identifying genes and their functions) from the pharmaceutical industry. Indeed, several established biotech players from the health care arena are already leveraging their know-how into plant biotech. Paris-based gene mapping firm Genset has sold rights to its technology for agricultural applications to a Los Angeles startup called Ceres. San Francisco's AxyS Pharmaceuticals, a gene and drug specialist, says it could be next.

"I think that you're going to see a huge number of startups, probably 20 to 30 new companies," says John Ryals, founder and CEO of Paradigm Genetics, a new plant biotech firm based in Research Triangle Park, N.C. "It's a wide-open opportunity right now." **—Antonio Regalado**

Commercial Seedlings Sprout in Agricultural Genomics

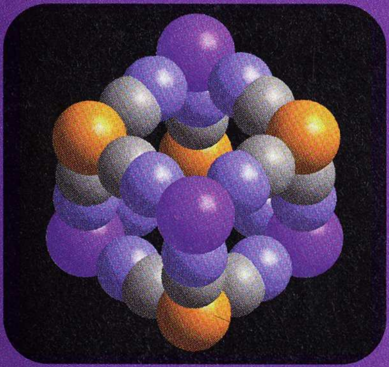
NAME	FOUNDED	LOCATION	
Metanomics	June 1998	Golm, Germany	Spin-out from Max-Planck-Institute of Molecular Plant Physiology
Ceres	Dec. 1996	Los Angeles	Technology alliance with human genomics firm Genset last January. Led by ag biotech veteran Walter De Logi.
Paradigm Genetics	Sept. 1997	Research Triangle Park, NC	Founded by ex-executives of Novartis Crop Protection. Raised $6 million in venture capital.
Mendel Biotechnology	Apr. 1997	Hayward, Calif.	Last November, Monsanto and Mexican seed-giant ELM each paid $15 million for access to Mendel's technology.
BioSource Genomics	Jan. 1998	Vacaville, Calif.	Robot-driven approach will test roles of 800 genes a day.

NANOTECH

Molecular Tinkertoys Yield a Box

Imagine building a house out of rope. It wouldn't be easy. Neither is building individual molecules into rigid, hollow shapes. In fact, one of the most simple of molecular geometries—a stand-alone cube—has so far eluded scientists.

Now, Thomas Rauchfuss, a chemist at the University of Illinois at Urbana-Champaign, and his co-workers have constructed a molecular box that mea-



THOMAS RAUCHFUSS

sures 5 angstroms on a side and 132 cubic angstroms in volume. Big enough to hold single atoms inside. The ability to trap atoms could one day enable the molecular box to function as a highly sensitive sensor.

The key to molecular box-building is a Tinkertoy strategy alternating two types of corners, explains Rauchfuss. One type of corner is a cobalt atom studded with carbon arms; the other type is a rhodium atom with nitrogen appendages. The carbon and nitrogen groups connect to form a stable cube. What's more, says Rauchfuss, the boxes are constructed in a way that allows them to exist as separate molecules.

The box joins a growing list of molecular shapes made by chemists in recent years. Examples include fullerenes—60 carbon atoms arranged like a geodesic sphere—and pipette-like carbon nanotubes. And there's no reason to stop at a box, says Rauchfuss. "We might make a bowl or maybe a giant tetrahedron next." —**Antonio Regalado**

MANUFACTURING

Teaching Iron New Tricks

BP's polyethylene plant in Indonesia.

BP CHEMICALS

IRON IS A JUNKYARD DOG AMONG METals—scrappy and hard working. But when it comes to the delicate task of acting as a catalyst in joining together the molecular pieces that make up plastics, chemists have long favored purebreds: exotic metals, such as zirconium. Now, two separate teams of chemists, one at Imperial College and BP Chemicals in London, and the other at the University of North Carolina (UNC) and DuPont, have made iron-based catalysts that excel at making plastics, particularly polyethylene.

The advance could mean a simpler and cheaper way to make common plastics. "They're really good catalysts in making polyethylene very rapidly," says Richard Schrock, a catalyst chemist at MIT. What's more, says Schrock, the catalysts are intriguing because it remains a mystery precisely how and why the iron works.

The chemists transformed iron into a catalyst by attaching to it nitrogen-containing groups. These groups wrap around the iron, but at the same time leave part of the iron exposed; this vacant spot allows monomers (the building blocks of polymers) access to the iron. When they made the structure, the researchers found to their surprise that the iron has a talent for stitching together the monomers.

Vernon Gibson, a chemist who headed the effort at Imperial College, says when he began the research "we didn't necessarily expect it to work." Gibson says that chemists often have slighted iron when looking for new polymer catalysts. "It was thought that there was no point in looking at iron. This opens up a new part of the periodic table."

To plastic makers, that new terrain looks a lot like a gold mine. Producing polyethylene is a multibillion-dollar business and being able to make it for even a few cents per pound cheaper can be a tremendous advantage. What's more, says Bill Tallis, director of technology at BP Chemicals, the iron catalysts could make plastics with improved properties. "We've seen enough to be very encouraged," he says. Encouraged enough that BP expects to test large-scale production of polyethylene using the iron catalysts later this year.

The current work is part of a large-scale effort to find more efficient and versatile catalysts for making plastics. A first generation of new catalysts began hitting the market in the mid-1990s. A second generation includes nickel and palladium catalysts discovered by UNC and patented by DuPont.

Will the iron catalysts emerge as yet another commercial breakthrough? It's too early to tell. Indeed, it's still unclear who has rights to the technology. The catalysts developed by the two groups are virtually identical, so it could come down to who first claimed them. "It will be very close," says BP's Tallis. **—David Rotman**

BIOMEDICINE

Running the (Bacterial) Film Backward

CENTER FOR BIOFILM ENGINEERING

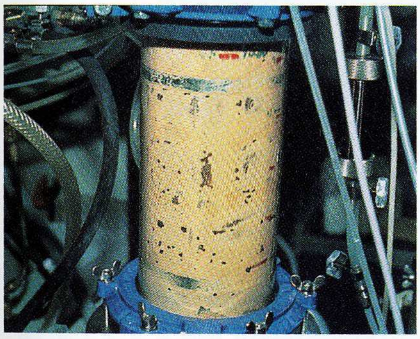
Bacteria are often pictured as lone cells moving randomly about. In fact, millions of bacteria frequently stick together in well-organized colonies. This is slime—or, as microbiologists prefer to call it, "biofilm." A research team at the Center for Biofilm Engineering at Montana State University (MSU) in Bozeman has now identified the chemical signal secreted by bacteria that tells the microbes when to form—and when to desert—these bacterial structures.

The discovery could provide clues on ways to shut down the formation of biofilms. And that could mean a potful of applications—including controlling bacterial infections in hospitals and controlling contamination of water supplies. As a result of these implications, the findings "are of considerable significance," says molecular geneticist John Geiger, group leader for biotechnology at Olin, a Cheshire, Conn.-based producer of industrial biocides.

The MSU group, headed by microbiologist David Davies, found that a common bacterium, *Pseudomonas aeruginosa,* secretes a chemical called homoserine lactone (HSL) that controls the development of biofilms. They suspect that biofilms created by other types of bacteria also depend on the chemical signal.

Based on the insight, the MSU group is already synthesizing and testing chemicals that disrupt the natural messenger system. And while the work is still in the early stages, the possibilities are almost endless. Biofilms grow anywhere there's water and a hard surface, forming mushroom-shaped pillars with protective slimy coatings.

Biofilms create countless medical problems, contaminating contact lenses, catheters and artificial implants. Biofilms of *P. aeruginosa* pose particular concerns—they are the chief cause of hospital-acquired infections; they also clog the lungs of cystic fibrosis patients. Another biofilm, dental plaque, corrodes teeth and is an obvious target. A chemical based on HSL "could be added to toothpaste or mouthwash," says microbiologist Bill Costerton, director of the Center for Biofilm Engineering.

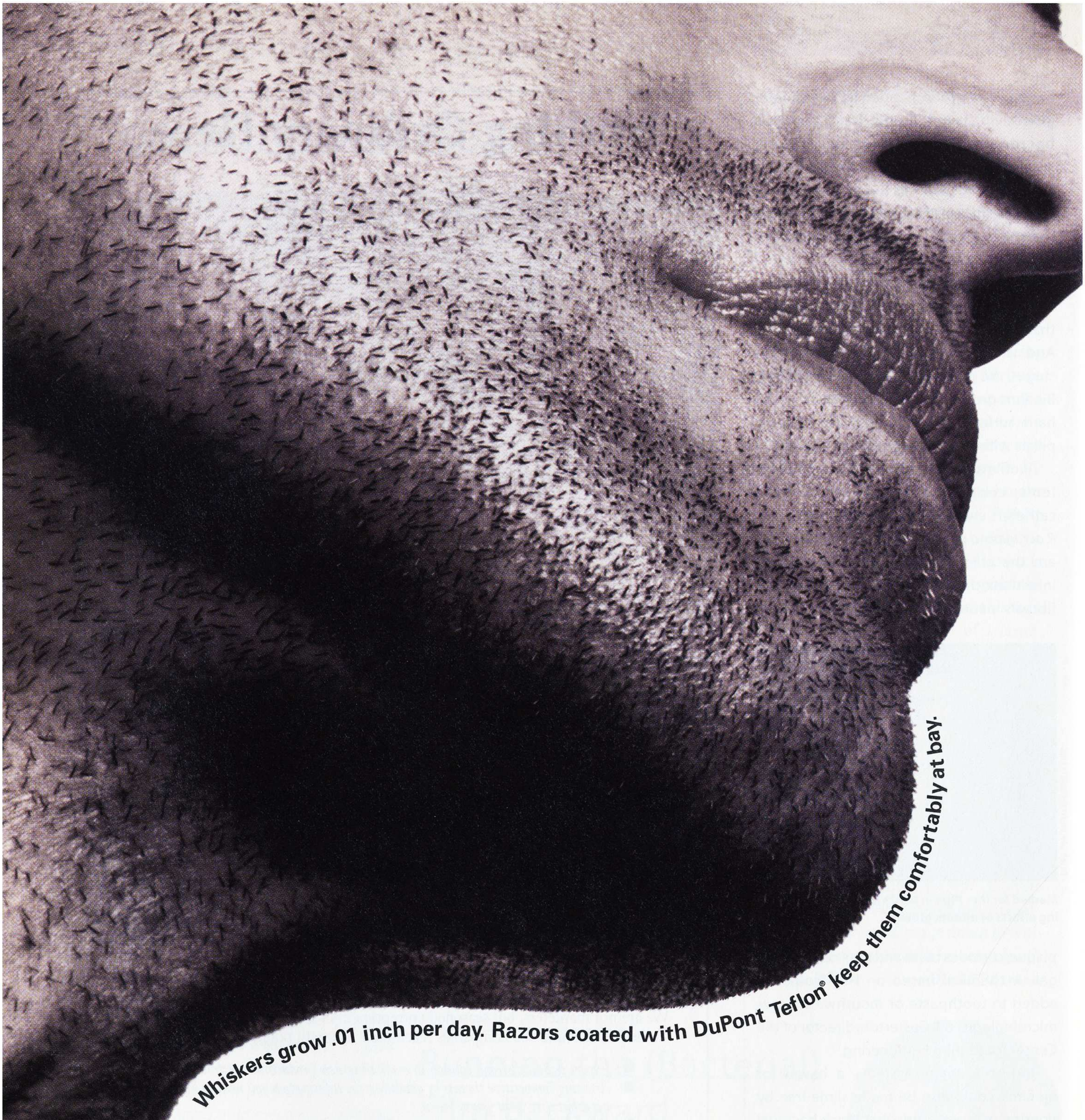


CENTER FOR BIOFILM ENGINEERING

Marked for life: Pipe in MSU's lab shows damaging effects of biofilm growth.

Industrial water systems, a haven for biofilms, could also be made slime-free by pouring in compounds that block bacterial congregation. Likewise, the MSU results could lead to safer chemicals to prevent biofouling on boats, replacing biocide paints that contain toxic heavy metals.

The long-held trend to kill problematic bacteria using antibiotics and biocides "has caused all kinds of problems like bacterial resistance. Now we can't even kill them," says Costerton. "Perhaps we can coexist with bacteria and manipulate their bothersome ways." Learning how to prevent them from forming their bacterial cities may be a first step in that direction. —**Carol Potera**



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The Rage for Global Teams

In technology, teams are tops. And for the most innovative companies, U.S.-only teams are old hat. Global teams are the rage. Consider the following:

- In Penang, Intel taps the talents of top Malaysian engineers, not only by hiring them as employees but also by helping them launch their own businesses—and then hiring the new firms as contractors who at times work alongside Intel's own employees.
- Engineers from Colorado, Australia, Germany, India and Japan converge on a hotel in trendy Los Gatos, Calif. This isn't a vacation but a rare face-off between members of a Hewlett-Packard software team.
- In Gemenos, France, a half-dozen French engineers at Gemplus, a leading supplier of smart cards, are managed by an American who speaks only enough French to converse with a waiter. His counterpart at Gemplus' research lab in Redwood City, Calif., is a Frenchman who manages a group of Americans.

In spite of some significant cultural and logistic obstacles, diverse global teams are the future of innovation.

The spread of global teams is probably inevitable, given the ease and inexpensiveness of communications. It also helps that engineers and scientists around the world share the same basic education. Many multinationals, meanwhile, run worldwide training programs that further the trend toward a shared mentality among the world's technical elite.

To be sure, there are plenty of barriers to global teamwork. Look at the life of Radha Basu, who manages Hewlett-Packard software teams that stretch across six countries and 15 time zones. Just communicating is a challenge. She tries to visit each piece of every team four times a year, flying more than 100,000 miles. She's on the road so much that she frequently sends a single five-minute-long voice mail to hundreds of people.

Though all her business is conducted in English, this common language can obscure cultural differences. When talking to an engineer in Brazil about deadlines, she must realize that a due date of Monday may mean that code will arrive any time that week. "By contrast, when one of my engineers in Germany commits to a day," she says, "he usually gives me a *time* of the day he'll deliver."

Jealousies across cultures can also undermine teamwork. In developing countries, engineers at some multinationals may resent their much-better-paid teammates in the United States and Europe. At one big disk-drive company, engineers in Thailand and Malaysia provide crucial process innovations that make mass production of new drives possible. Yet they fume privately that their American teammates consider them less creative and resist giving them more demanding assignments.

Not surprisingly, some companies eschew global teams altogether. Microsoft, for instance, keeps all its teams within its sprawling campus in Redmond, Wash. It only recently announced plans to open its first non-U.S. facility—and this will be a laboratory in "exotic" Cambridge, England.

Despite the inherent risks and difficulties of global teams, they are increasingly popular. The reason is simple: With demand red-hot for skilled engineers, companies have more incentive than ever to build their ranks abroad. After all, there are only so many code writers and hardware jocks that can be brought legally into the United States. Besides, it's expensive to import foreign talent, and engineers in their native lands are usually a bargain (the exceptions: those in Western Europe and Japan). From Seoul to Singapore, engineers earn roughly one-third to one-half of their American counterparts. Indian or Russian engineers, meanwhile, are happy with a paycheck that is one-tenth of what a Yank gets.

"Discount" foreign engineers often are assigned to banal tasks such as teasing another model out of an aging hardware line or writing ancient COBOL code for so-called "legacy" software. But companies are increasingly making foreign engineers, even those from developing countries, equal members of far-flung technical teams.

While multinational companies say they can't offer equal pay to top team members in the developing world, they can shower them with perks. In another unit of Hewlett-Packard, for instance, a star Malaysian engineer in Penang lives as if he were in Silicon Valley. He has a posh pad, a new car and trendy holidays such as a weekend of rock climbing. He also gets bonuses, stock options, special equipment at work and a high-powered ISDN line and a computer at home. The company even periodically flies him to see teammates in California. All this effort is expended simply to keep him happy on his own turf.

When global teams work, the results are impressive. Product cycles are cut in half; Ms. Basu says her teams either write code or test it an average of 22 hours a day. Different parts of the world, meanwhile, specialize in different techniques. They can also cater to the needs of customers in the region.

Such global teamwork isn't going to win Ms. Basu a Nobel Peace Prize, but it is good business. Despite the inevitable headaches, bringing diverse people together is the future of innovation. ◊

If this elusive creature is found, it could revolutionize medicine. But to reap the rewards, biotech firms and researchers must brave a firestorm of controversy. BY ANTONIO REGALADO

The Troubled Hunt

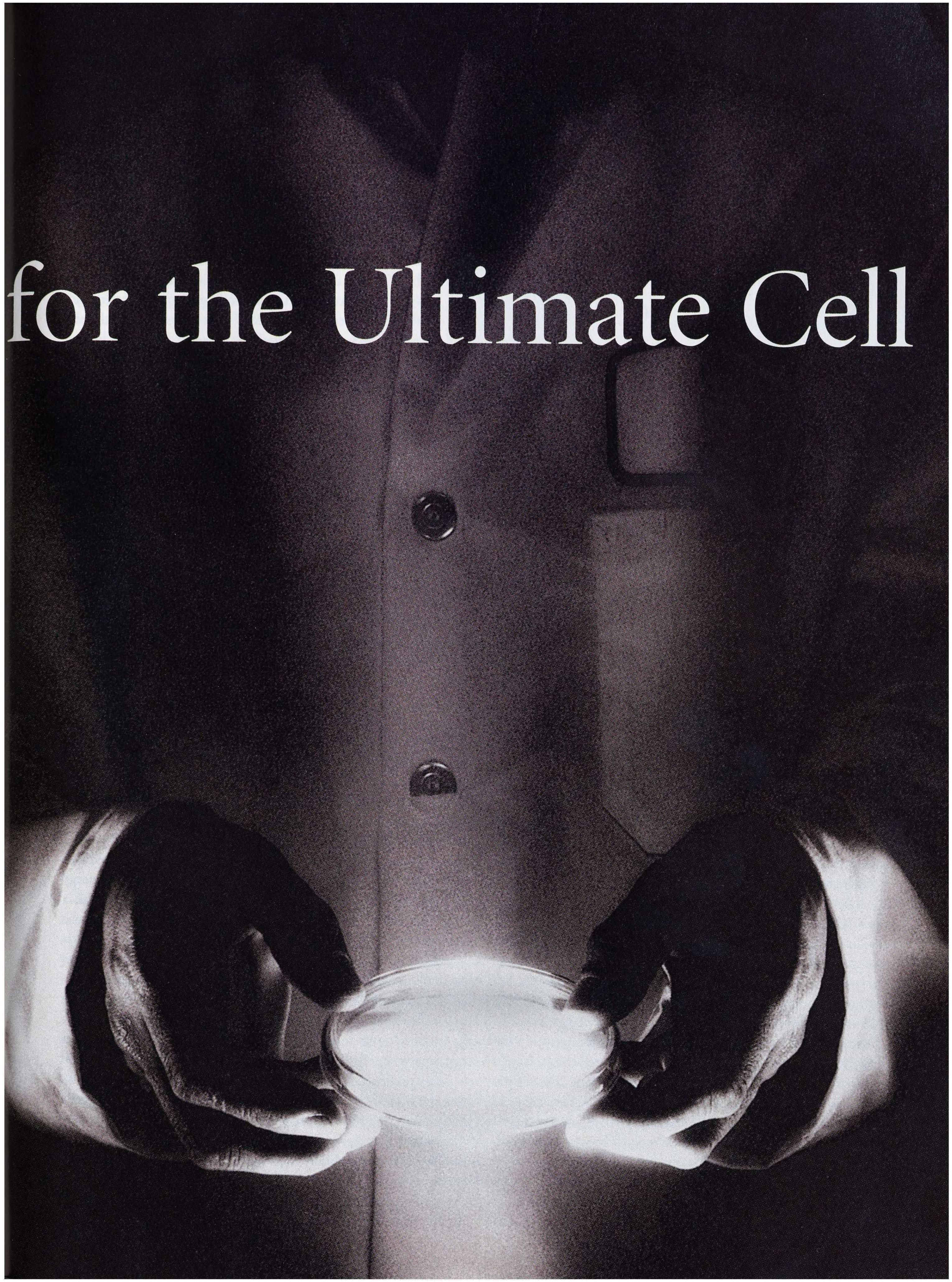
John Gearhart's lab is closed to outsiders.

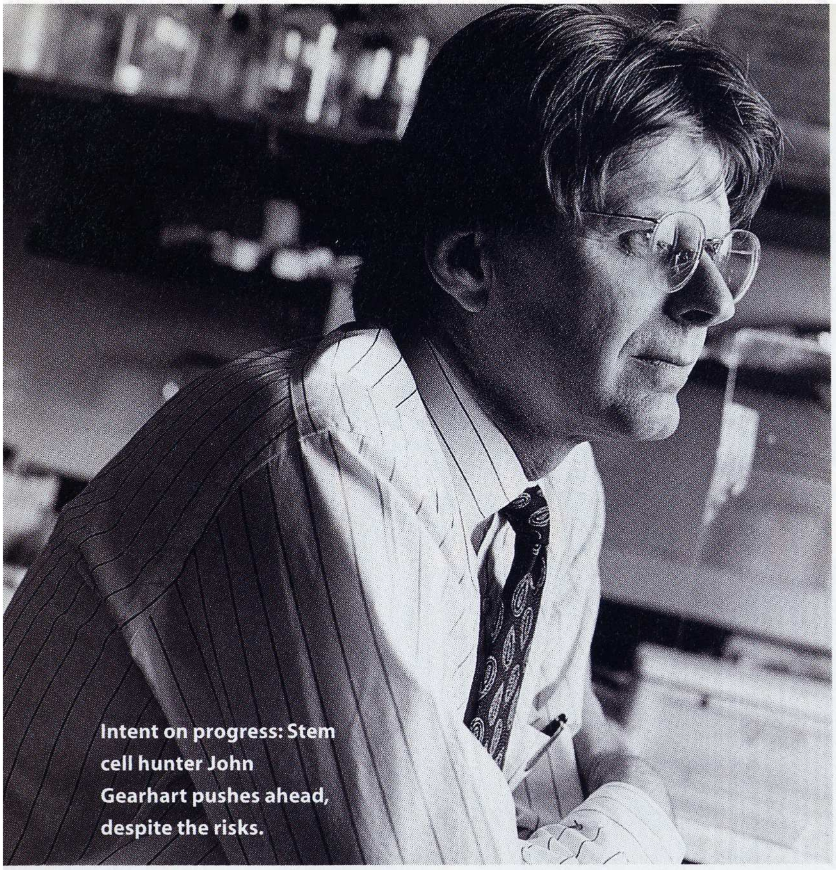
Rather than happening there, an interview brokered by a university public affairs officer takes place in a windowless lecture room in the bowels of the Johns Hopkins University School of Medicine. Outside, seedy east Baltimore vibrates with the energy of a bright spring day. Gearhart appears and takes a seat under the fluorescent lights. Time is short, and no tape recorders, please.

With reddish blond hair and a direct gaze, Gearhart speaks with excitement about the vast medical potential of the research going on in his lab. He describes the early stages of human life and an elusive cell found only in embryos. But there's much about this conversation that's fleeting, incomplete and evasive. Suddenly his voice turns defiant and he's scowling deeply. He relates how he and his family have received threats, how other scientists have criticized his failure to publish and his close ties with industry. And then he is gone, sprung by the clock-conscious PR man.

If awards were given for the most intriguing, controversial, underfunded and hush-hush of scientific pursuits, the search for the human embryonic stem (ES) cell would likely sweep the categories. It's a hunt for the *tabula rasa* of human cells—a cell that has the potential to give rise to any of the myriad of cell types found in the body. If this mysterious creature could be captured and grown in the lab, it might change the face of medicine, promising, among other remarkable options, the ability to grow replacement human tissue at will. The ES cell could, scientists hope, be a factory-in-a-dish that turns out cardiac muscles to patch heart attack victims, neurons to mend paralysis or pancreatic cells to battle diabetes. "It's a treasure house of opportunity for developing fundamental knowledge and medical applications," says Michael McClure, chief of the Nation-

PHOTOGRAPHS BY ROBERT CARDIN


for the Ultimate Cell



Intent on progress: Stem cell hunter John Gearhart pushes ahead, despite the risks.

PETER HOWARD

al Institute of Child Health and Human Development's Reproductive Sciences Branch in Bethesda, Md.

That all sounds so promising. Why, then, is John Gearhart besieged? The answer is that these cells are found only in embryos or very immature fetuses, and pro-life forces have targeted the researchers who are hunting for ES cells, hoping to stop their science cold. In addition, the federal government has barred federal dollars for human embryo research, pushing it out of the mainstream of developmental biology. To make matters worse, human ES cells could conceivably provide a vehicle for the genetic engineering of people, and the ethical dilemmas surrounding human cloning threaten to spill over onto this field. Deprived of the federal funds that power most basic biomedical research and surrounded by fierce controversy, the hunt for the ES cell is being undertaken only "by a few brave souls," says Colin Stewart, a colleague of McClure's at the National Institutes of Health (NIH).

Extensive reporting by *TR* suggests that in the United States, those brave souls are drawn from fewer than a half-dozen research groups. There are also a few others in the United Kingdom, Australia and Singapore. Even this intensive survey may have missed some researchers, since some probably prefer to do their work in silence. "We're constantly wondering what our competitors are doing, and even who they are," says Gearhart, director of research at the Johns Hopkins department of gynecology and obstetrics.

Taming the human ES cell wouldn't just be a huge scientific coup—it would also be a potential gold mine for the biotech firm that took out an enforceable patent on the *tabula rasa* cell. But the same secrecy and controversy that dogs the researchers has also limited the open involvement of industry. Just one company is openly chasing the human ES cell—Geron of Menlo Park, Calif. This young Silicon Valley firm has aggressively signed collaborations with leading ES researchers, including Gearhart and Roger Pedersen, a reproductive biologist at the University of California, San Francisco (UCSF). A search of the U.S. patent filings also shows that a small startup in White Plains, N. Y., called Plurion, is building up intellectual property around the ES cell. But Plurion executive Mark Germain declines to comment further.

"It's a taboo area," says Doros Platika, CEO of the Cambridge, Mass.-based startup Ontogeny, a rising star in the developmental biology business. "Big pharmaceutical companies are afraid to touch it. And the field needs to sort itself out before we'd get into it."

In spite of all these difficulties, there is a healthy scientific competition to catch the human ES cell—driven both by the desire for scientific glory and by the riches that might come with controlling the fabled stem cell itself. "It's a race. I lose sleep," Gearhart says. And despite many technical difficulties, several labs—including Gearhart's—believe they may already have captured the ES cell and are working to characterize and control the cells, furiously filing patent applications as they go.

Furious scientific competition, threats of violence, huge medical potential, fear and secrecy. Welcome, behind closed doors, to the topsy-turvy world of the human embryonic stem cell.

A Breakthrough

The prize in this hunt is an invisibly small translucent dot found on the inside of an early stage of the human embryo, known as the blastocyst. Several days following fertilization, the blastocyst, a hollow ball of about 140 cells, rolls out of the fallopian tube and into the uterus, to be implanted there. Clinging to the inside of this rolling sphere are a group of identical cells—the ES cells—which are the starting point of the fetus. Soon they will divide rapidly and their descendants will take on increasingly specialized roles, emerging as heart, muscle, blood, bone, hair, nerves and all the rest of the human apparatus. For now, though, they are pure potential: holding the capacity to become any part of the body. And therein lies their mystery and their biomedical significance.

Biologists, understandably, are fascinated. But before they can study this primordial cell, they need to capture it—and control its growth—in the laboratory, something that hasn't proved easy to do. Like physicists studying particles present at the birth of the universe by recreating its initial conditions in high-energy colliders, biologists are attempting to isolate the ES cell with a concoction of powerful biological substances that mimic those present in the first days of life.

The science behind ES cells began in earnest in 1981, when researchers in Great Britain and California independently succeeded in isolating a curious kind of cell from the interior of the mouse blastocyst. These embryonic cells were identical but each had the potential to give rise to an enormous range of different cell types—a defining mark of a stem cell.

Researchers learned how to tame the mouse ES cell in its pristine, undifferentiated state by growing it in a bed of special cells bathed in blood serum from a calf; added to the stew is a selection of proteins called growth factors. In the potion is a signal telling the ES cells not to differentiate—since their capacity to remain undifferentiated is the key to exploiting their practical potential.

Seeing the success in rodents, researchers soon began searching for ES cells in other animals, such as cows and pigs. But that

Thousands of transplant patients now die waiting for a donor match. Human embryonic stem cells might save many of their lives.

turned out to be a difficult task, because the stem cells don't hang around for long. "It's in their very nature to want to become something else quickly, and it's very difficult to hold them back," says James Thomson, a biologist at the Wisconsin Regional Primate Research Center at the University of Wisconsin.

For more than a decade, the mouse ES cell stood alone. But patient, painstaking work in a number of labs slowly led to success, and reports of ES cells in other species began trickling in (see page 40).

However, by the early 1990s, no primate ES cells had been isolated. Then, in 1994, came a breakthrough. Thomson succeeded in isolating ES cells from the Rhesus macaque monkey. The discovery was a provocative hint that it might be possible to find the ES cell of another—even more interesting—primate. The race was on.

UCSF's Pedersen decided to go after the human ES cell in 1994 after becoming intrigued by his colleagues' success in growing specialized tissue, including neurons, from mouse ES cells in the laboratory. "I got fascinated with the potential" for growing transplantable human tissues, says Pedersen. He also points to a more personal motivation. When his daughter was 4 years old, a playmate of hers named Michelle Platt-Ross died of SCID—a catastrophic developmental failure of the immune system treatable only with a transplant of perfectly matched bone marrow. Like thousands of other transplant patients, Michelle had died waiting for a donor. The ES cell looked like a possible solution to those heartbreaking cases because it could—at least in theory—provide a nearly universal source of transplant tissue. "It was clear to me that if there was any way I could help a girl like Michelle, I would grab it."

Pedersen started a low-key quest to isolate ES cells using funds from his department and studying embryos donated from UCSF's *in vitro* fertilization (IVF) clinic, where he serves as director of research. But soon Pedersen was looking to step up the effort. Deprived of federal funding, he accepted research backing from Geron, which had already jumped into the race by licensing rights to Thomson's Rhesus cells, and received his first check from the biotech company in early 1997.

Like everyone in this field, Pedersen isn't voluble about his work; he refuses to talk specifics about his progress. But he does note that he needs to make progress quickly, since his grant from Geron is for only two years. That kind of time frame is "quite a demanding hoop to jump through with any new technology," says

Embryos and Ethics

What do you get when you put an ethicist, a Methodist minister, a futurist, a theologian and a Judaic scholar together? In this case, the answer isn't a punchline: it's Geron's newly formed ethics advisory board.

Biotech companies often hire scientific advisory boards to help them anticipate and overcome technological challenges. But Menlo Park, Calif.-based Geron is leading the push to isolate the human embryonic stem (ES) cell and hopes an ethics panel will help it stave off public opposition to this controversial research. Arthur Caplan, director of the Center for Bioethics at the University of Pennsylvania Medical Center, thinks Geron is on the right track. "If they [proceed] without this discussion they are going to have to make their products behind very thick walls and in very deep bunkers," he says.

The main source of controversy is that ES research usually involves the use of human embryos, which pro-life groups vehemently oppose. As a result of the pressure, there's been a *de facto* ban on federal funding of such work since 1978. The climate has scared off all but a few of the best scientists, says Ronald Green, director of the Ethics Institute at Dartmouth College and professor of religion. But instead of stopping embryo experiments, the funding ban has simply curtailed federal oversight, according to Green. "You create an environment where people work without scrutiny," he says.

ES researchers working with private funds, such as Roger Pedersen at the University of California, San Francisco, who's funded by Geron, have had to find their own way through the ethical maze. For Pedersen, using extra embryos donated from *in vitro* fertilization clinics is acceptable, but creating new embryos specifically for the purpose of research isn't.

But many other researchers aren't willing to walk this fine line, especially when their NIH funding could be at stake. Last year Mark Hughes, a senior Georgetown University geneticist, lost his NIH grants and his job after using government-funded postdocs and equipment to perform routine diagnostic tests on embryos. Pedersen says he must now be extremely careful to maintain an "extreme and absolute" separation between his ES work and NIH-funded research projects. The divide affects everything from chemicals to staff, Pedersen says.

In addition to the embryo debate, Geron's ethics team will have to confront public fears that the potent ES cells might be misused to create designer humans or bizarre human-animal combinations. Last December, longtime biotech critic Jeremy Rifkin filed a patent laying claim to methods for making chimeras by implanting human ES cells into animal embryos. Rifkin hopes to block any Dr. Moreau seeking to profit from such hybrids.

A far-out idea? Not necessarily. Scientists already insert human genes—even whole chromosomes—into animals to make useful research species. Rifkin's patent is partly a PR stunt. He wants society to address the question, "How far can we humanize other creatures and then claim them as intellectual property?"

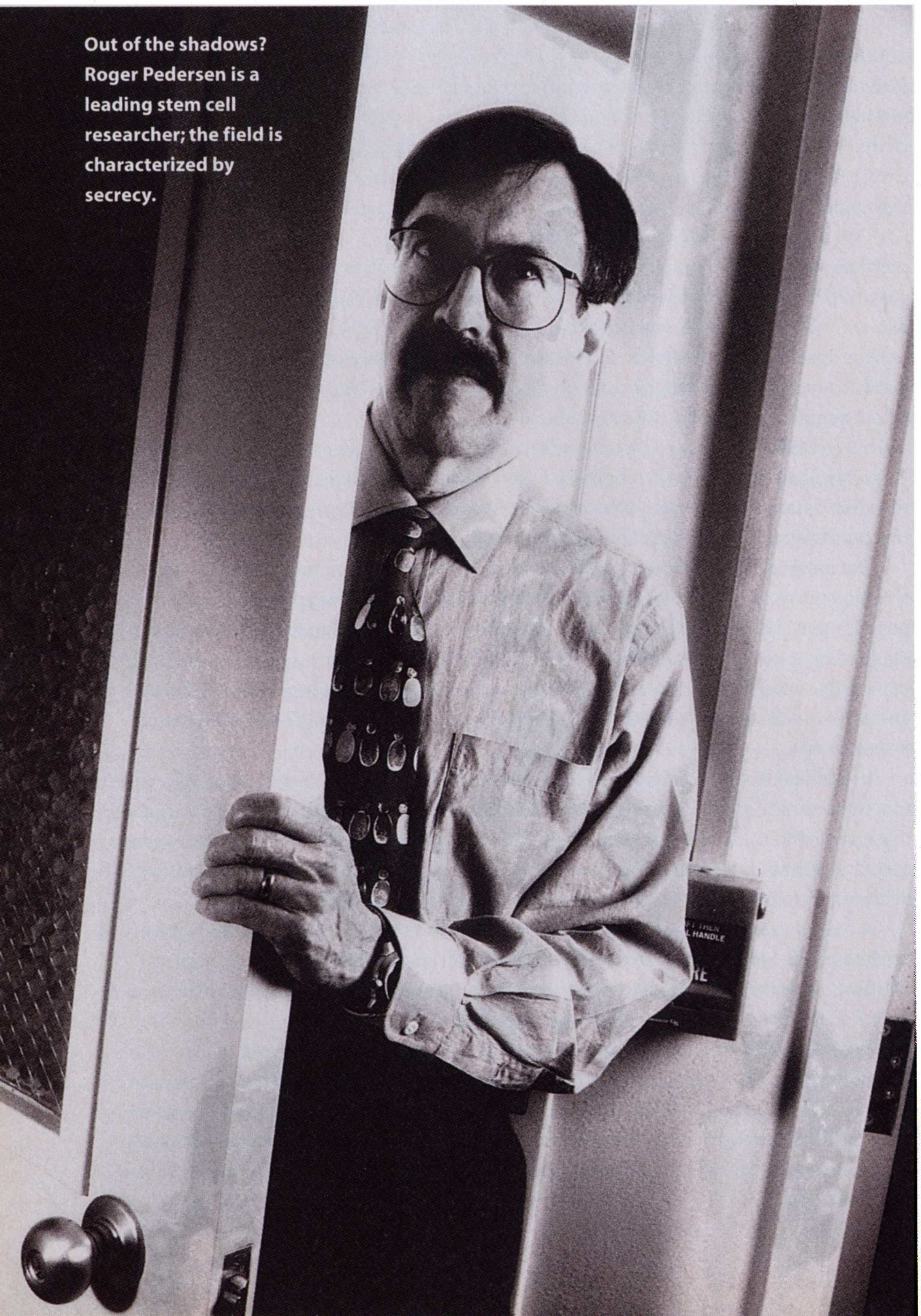
For Rifkin, the biotech revolution is troubling because it is being waged in an industrial setting where life is subjected to engineering rather than ethical principles. By appointing an ethics board, Geron is hoping that the two sometimes competing perspectives can be reconciled. And while it's a complex and often abstract kind of dialogue, the future of ES cell research—and all the remarkable possibilities that go with it—could be riding on this discussion.

In addition to its remarkable medical potential, the embryonic stem cell would open an invaluable window onto the basic biology of human development.

Pedersen. The first obstacle was simply learning how to grow the 4-to-8 cell embryos that the group gets from the IVF lab to the blastocyst stage, where ES cells should be found. "This is how basic the problems are," Pedersen explains. "It's not like shooting fish in a barrel."

But skill in trapping the ES cells in the lab is likely to be only one factor in deciding who wins the race. Perhaps the most critical resource (and the one that effectively prevents some labs from joining this race) is access to human embryos. "There is a paucity of material available for research," explains Mark Perloe, director of Reproductive Endocrinology and Fertility at the Georgia Baptist Medical Center. "When someone is laying out $8,000 to $10,000 for IVF, it's unlikely they'll donate extra embryos to research." Instead, he says, patients generally have the extra embryos frozen for later use, or simply destroyed. "They don't want anyone else making money off their babies, and that's how they look at them—as their babies and not as a cell."

Indeed, some believe that access to healthy embryos may determine who finds the ES cell. "I would guess whoever has good stem cell experience and happens to land next to a good IVF lab will be successful first," says Thomson. And even for those who have access, not all access is equally valuable. Thomson is hoping to repeat his Rhesus success in humans but says that his collaboration with the IVF lab at the University of Wisconsin in Madison hasn't put him at the front of the pack. "Madison is a small community, and the number of embryos donated is minuscule."



Out of the shadows? Roger Pedersen is a leading stem cell researcher; the field is characterized by secrecy.

Potentially, embryos could be produced and grown in the lab by simply fertilizing unwanted eggs. Although the Federal government won't fund such practices, in most states there is no law against doing it with private money. But Pedersen, for one, has ethical qualms about fertilizing eggs just for research purposes. "It might come to the time when we do it that way, but it pushes some of our own ethical buttons," he says. "We haven't wanted to cross that line yet. It's a very gray area."

Into the Fire

Back in Baltimore, Gearhart had adopted a radically different strategy—and one that appears to have propelled him to the front of the pack. He decided to sidestep the use of blastocyst-stage embryos altogether as a source of ES cells. The deciding factors were both political and scientific. The government's funding ban, combined with the poor quality of available embryos "turned me away from that approach," he says.

Instead, Gearhart picked up on a technique devised by cell biologist Brigid Hogan at Vanderbilt University Medical School. In 1992, Hogan showed that so-called primordial germ cells from the genital ridge (terrain destined to develop into the testes or the ovaries) of a mouse fetus could be grown in culture and acted much like ES cells. She hypothesized that the same approach might work in humans. Using aborted fetuses donated by patients, Hogan managed to isolate some interesting cells but wasn't able to establish permanent cell lineages growing in culture—a key aim of ES research.

This alternative approach circumvented some of the funding and scientific difficulties of working with embryos. Yet in some ways it was a case of jumping out of the frying pan into the fire, since researchers using aborted fetuses are exposed to the same risk of violence from anti-abortion activists that abortion clinics face. "The threat to people working with fetal material is very real," says Hogan.

Nevertheless, Gearhart took this strategy and ran with it—possibly all the way to the finish line. In July 1997, at the 13th International Congress of Developmental Biology in Snowbird, Utah, which was still abuzz from Ian Wilmut's announcement that February that he had cloned a sheep named Dolly, Gearhart told a special ethics forum that he and postdoc Michael Shamblott had been growing "ES-like cells" in their lab for the preceding six months.

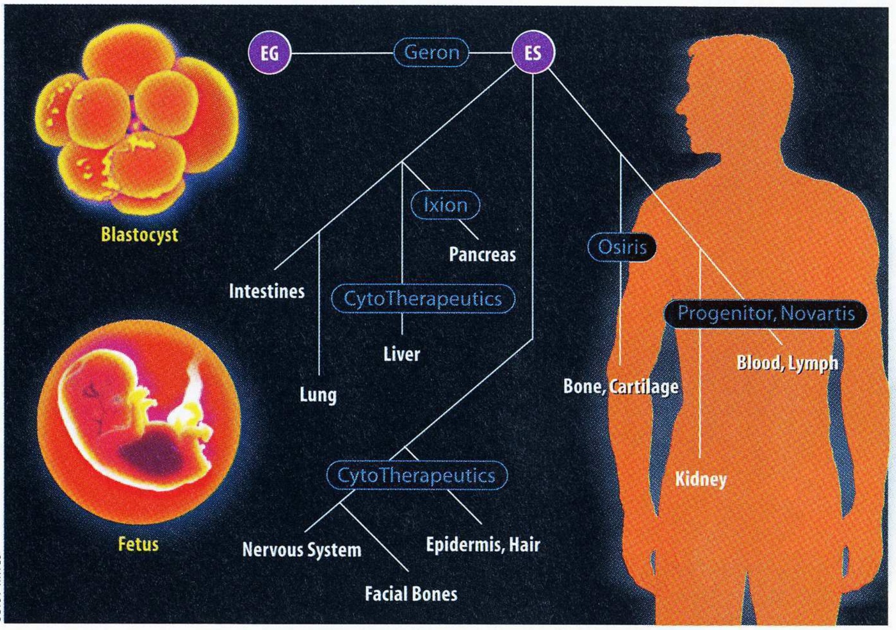
The connection between the ES cells and Dolly was more than just a coincidence of timing: Human ES cells could, in principle, be the vehicle for creating new breeds of human beings, as the mouse ES cells have already been used for mice. Gearhart, however, assured some attendees that neither he nor his colleagues had any intention of producing genetically altered people. His focus, he said, is strictly on the cells' potential for saving lives by growing replacement tissues and organs and by providing important tissues for medical research. Yet even Gearhart's colleagues understand where the fear of this new technology comes from. "It's so easy to imagine the bad applications, since the misuse of technology, the Frankenstein myth, is already part of the vernacular," says Pedersen, who chaired the ethics session at Snowbird.

Is Gearhart the winner in the race for the human ES cell? That's not an easy question to answer. He and his collaborators say they have succeeded in growing "ES-like cells" from 5-to-9-week-old fetuses and are sustaining them in cell culture. But, in keeping with the field's atmosphere of secrecy, Gearhart's lab hasn't yet published its results. The difference between these fetal germ cells and ES cells may well turn out to be a bone of contention among labs in the race. Gearhart, for his part, remains confident. "For all practical purposes," he believes, these cells and ES cells will turn out to be "equivalent."

Whether Gearhart has already won the race behind closed doors or not, the benefits for medicine of having a winner will be very large, with the largest payoff probably coming in the area of growing replacement tissues and cells.

Thomas Okarma, director of Geron's cell therapy programs, says replacement tissues for transplant will likely be the "big hit" for human ES cells. The first type of transplantable cell Geron hopes to make are heart cells. Okarma imagines inserting a "cassette" of genetic instructions into an ES cell that would direct it to turn down the differentiation path to heart tissue. "The cells could be injected directly into the failing part of the heart," Okarma says. The result could shore up failing heart tissue, nursing heart-attack victims back to health or providing a stop-gap for patients waiting for the right heart for a transplant.

Although Okarma envisions "a fermenter full of cells" derived from ES cells that someday will pump out new heart tissue, he stresses that the research is at an extremely early stage. To give some sense of how early, he tells *TR* that he hopes that within three years Geron will be testing the heart-tissue approach, using ES cells from Rhesus monkeys transplanted into other monkeys.



BETSY HAYES

Picking from the tree of life: Adult organs and tissues are descendants of embryonic stem (ES) cells found in the early embryo, or blastocyst. Embryonic germ (EG) cells found in fetuses may share the properties of ES cells—Geron is studying both types. As indicated, other biotech companies are working to identify intermediate stem cells responsible for repairing wear and tear on specific body parts, such as lungs, livers and bone.

But the benefits of identifying and cultivating the ES cells are not only practical; there will be substantial rewards for science as well. "In theory," says Okarma, "we should be able to generate an infinite and stable supply of [normal] human cells." In addition to their clear medical uses, these cells, which could be turned into particular types of tissues at will in the laboratory, would be hugely useful in research. Liver cells might be used to study drug metabolism and toxicity, while other cell types might be used to test the efficacy of drug candidates. A combination of ES cell and genetic engineering techniques could also generate many interesting cell lines. Just one example: brain neurons that quickly develop the type of amyloid plaque associated with Alzheimer's disease, providing an invaluable system for testing potential drugs to treat the ailment.

The ES cell could also open an invaluable window on human development, partly because developmental biologists would like to know which genes tell an ES cell to differentiate into more specialized cells. The proteins coded for by such genes could turn out to be new targets for drugs, or in fact be used as drugs themselves to spur, say, the regeneration of worn-out cartilage, or even to grow back receding hair.

Although the scientists at Geron are optimistic that they will be able to deliver on these promises, not everyone shares that upbeat state of mind. In spite of the apparent recent progress, some researchers who have worked with embryonic human cells doubt biologists will learn to control their growth anytime soon. H. Ralph Snodgrass, former chief scientific officer at Geron's Menlo Park neighbor Progenitor, says, "It's one thing to say the cells have the capacity to differentiate into all these cell types; it's quite another to exploit that. There are some significant hurdles."

Snodgrass is in a position to understand the practical difficulties. In the early 1990s, Progenitor, a biotech firm that also specializes in developmental biology, worked with human blastocysts, hot on the trail of the ES cell's close cousin—an undifferentiated version of the hematopoietic stem cell (which gives rise to the full complement of cells in human blood). But Snodgrass recalls that Progenitor's scientists couldn't control the embryonic cell on anything other than an experimental scale—developing an actual therapy that could withstand the scrutiny of the Food and Drug Administration seemed out of the question. Progenitor has largely dropped that effort, and now focuses on better understanding the genes that control the development process in mouse embryos.

Even those who aren't quite as skeptical as Snodgrass point out that there may be an easier route to finding a cell that could be useful as a source of replacement tissue. The shortcut involves

Which comes first? The chicken, or the egg? (Or the embryonic stem cell?)

Picture a chicken's egg. Now replace it with Michael West's vision for an egg. It's low in cholesterol and doesn't need to be refrigerated. It still comes in a carton but is laid by a chicken that is resistant to both Marek's disease—a scourge that kills off entire flocks—and to the *Salmonella* bacterium. Most important, it's packed with a drug vital to your well-being.

"We think this is the future of the poultry industry," enthuses West, CEO of Origen Therapeutics, a Palo Alto, Calif., firm that he founded last fall with $1 million in startup funds.

These future plans are being laid thanks to the chicken version of the embryonic stem (ES) cell—a cell that can give rise to any other specialized type of tissue in the organism. Origen's academic partner James Petitte of North Carolina State University isolated the slippery chicken ES cell, and West predicts his firm will soon do the same for the ES cells from other poultry and farm animals. The cells give scientists a blank slate to easily introduce permanent genetic changes into the animals, while "knocking out" undesired traits. "We have the door open in front of us to do really sophisticated, impressive genetic alterations," says West.

Origen's vision for finer fowl includes chickens with genes to make them more meaty as well as disease-resistant. But the biggest prize lies in turning the egg into an oval pharmaceutical factory. West says the company plans to engineer chickens that lay eggs packed with protein-based drugs that can be easily harvested by drug companies. Chickens are "the most efficient protein producing machine known to man," says West, who suggests that protein-based drugs could be produced for pennies.

ES cells are not the only tool for engineering genetic changes in animals, but thanks to some key properties they are an extremely potent one. First, ES cells grow tirelessly in culture, giving researchers ample time to add or delete DNA precisely. Then, when a genetically modified ES cell is fused into a developing embryo, it will grow to form some or all of the animal's tissue; through subsequent mating, pure breeds are made.

Origen's work with poultry could be only the tip of the transgenic iceberg. Research groups recently claim to have found ES cells in species ranging from the rabbit to the Rhesus monkey (see table). Leading the charge are startup companies like Advanced Cell Technology of Worcester, Mass. The firm was founded by University of Massachusetts biologist James Robl, whose lab succeeded in capturing ES cells from the cow and the pig. Robl says the pig ES cell might be the key to using animal organs for transplant into humans. Putting pig hearts or kidneys into people hasn't worked well until now because the human immune system is acutely sensitive to certain molecules on the pig organs. Robl, however, hopes to breed pigs free of these molecules.

Origen's West likens the ES cell to a computer breadboard and says there's no limit to the number of new circuits that can be built by reshuffling genetic components among species. "There are literally millions of inventions to be made," he says.

Embryonic Stem Cells: The Commercial Sector*

COMPANY (year founded, status)	LOCATION	TYPE OF CELL
Geron (1990, public)	Menlo Park, Calif.	Human, **Rhesus monkey**
Plurion (NA, private)	White Plains, New York	Human
Infigen (1997, private)	DeForest, Wisc.	**Cattle**
Advanced Cell Technology (1996, private)	Worcester, Mass.	**Cattle, pig,** human
Origen Therapeutics (1997, private)	San Francisco, Calif.	**Chicken,** other poultry and farm animals
Stem Cell Sciences (1994, private)	Monash, Australia	Pig, rat
Midas (1995, private)	North Grafton, Mass.	Pig
Avigenics (1996, private)	Athens, Georgia	**Chicken,** other poultry
Biotechnology Rsrch & Development (1998, public)	Peoria, Ill.	**Pig**

* Includes fetal-derived cell lines; NA= not available; Bold indicates companies claiming success in given species. For others, research continues.

Risky Business. Geron's CEO Ronald Eastman (left) and Vice President of Cell Therapies Thomas Okarma (right) lead the company's bid to capture and commercialize the embryonic stem cell. The company has formed collaborations with leading researchers in the field. Geron has previously bet heavily on speculative novel treatments for diseases of old age, such as Alzheimer's—they're used to taking risks on new science.

stem cells that have already changed into a cell family, say bone or nerve, but have not yet given rise to a specific type of cell. These stem cells are a step further down the differentiation tree from the embryonic stem cell. And many scientists believe they could be far easier to isolate (partly because they are still present in adults) and nearly as useful as a source of tissue for therapies involving replacement tissues.

With so many uncertainties and questions remaining, no one is ready to declare the race for the human ES cell over or predict the winner. And it could take years to sort out the competition. Proving one has the ES cell, or even an "ES-like" cell, is no easy task since no one is exactly sure what it should look like.

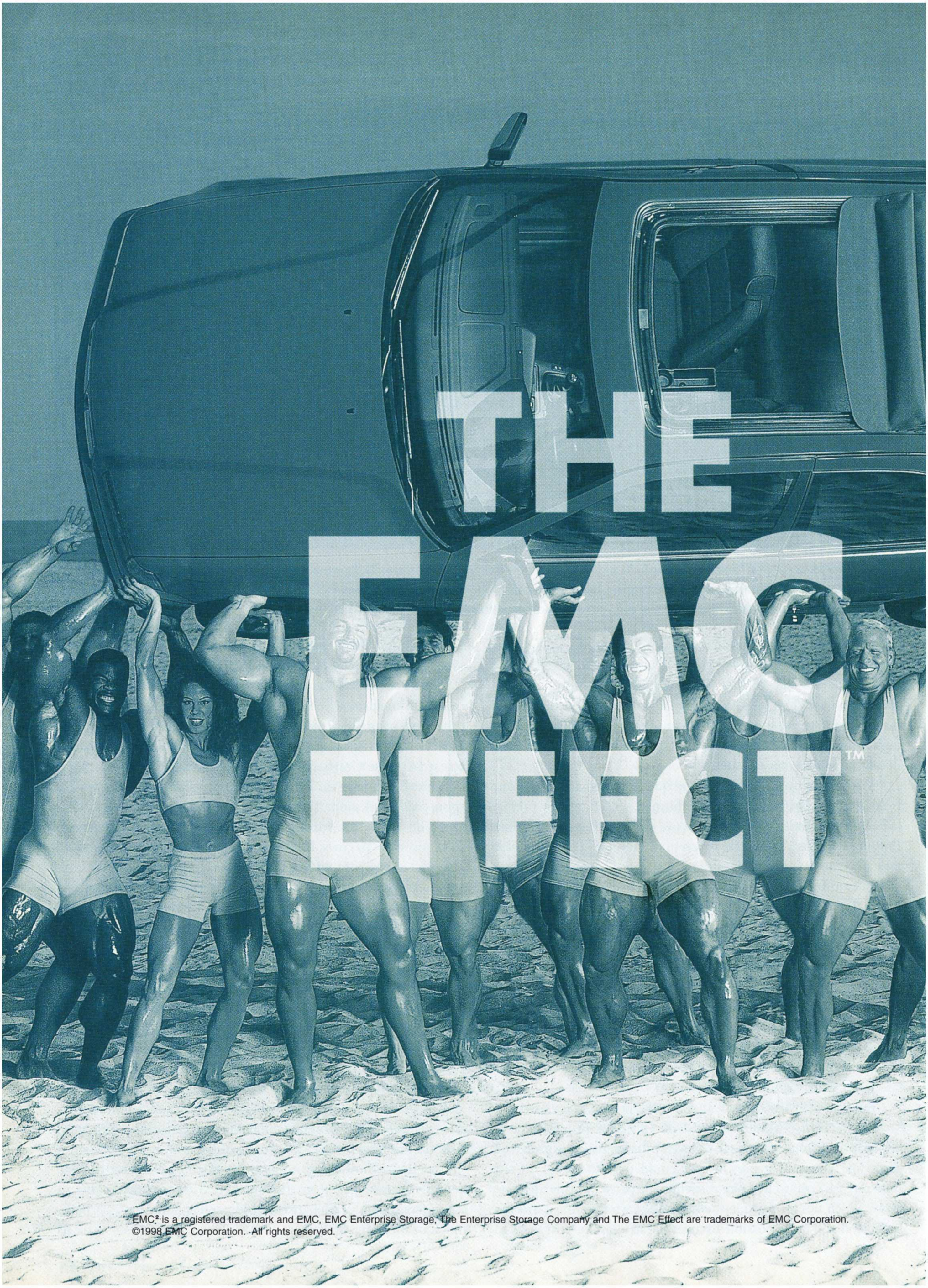
According to James Robl, a biologist at the University of Massachusetts who recently saw presentations from several ES research groups at a meeting in Australia, "The cells that I have seen don't look pretty, and they don't look like ES cells. But we'll just have to wait and see." Gearhart, for one, says that he's hard at work amassing publishable and patentable proof of his cell's powers. He is pushing to show that the cells can form most or all human tissues. The first test, says Gearhart, is to grow the cells in a dish and see what they make. ES cells from mice readily form blood and even beating heart cells. Gearhart says he's seen similar tissues from his human cultures.

But the ultimate test of an ES cell's power, says Gearhart, "won't be done." As in mice, that ultimate proof involves implanting human ES cells in a developing embryo, producing a germ-line chimera: a person that could pass the traits of the implanted ES cell to its own offspring. Deprived of this ultimate assay, which lies far outside the bounds of what's ethical or even feasible, it will be impossible to meet the strictest definition of an ES cell. But, when Gearhart looks at the composite picture provided by the other tests, he says, "We're convinced."

But convincing the establishment of mainstream developmental biologists will take some doing. Indeed, even getting other top scientists to publically consider the evidence may be difficult. In a glaring example of the silence enforced on researchers like Gearhart, the world's leading ES cell researchers descended this May on the University of Wisconsin for an NIH-sponsored workshop. The first of its kind, the conference featured ES specialists working on the whole animal kingdom—from monkeys to cows. But the human ES cell was just too hot to handle: No presentations on human ES cells were allowed.

Speaking from Scotland days before the start of the conference, Austin Smith, an ES cell hunter at the Centre for Genome Research at the University of Edinburgh, said, "I understood it was to be a meeting about the human ES cells and prospects thereof." That's why Smith agreed to deliver the keynote address, and why he recommended that Gearhart and other human ES cell researchers be asked to speak. "Then they [the NIH] called me to say they couldn't invite these people. So it's officially not about human ES cells."

But Smith predicted that human ES cells would be a subject of intense—if unsanctioned—discussion. In restaurants, bars, and in hallways...everywhere but in the official sessions themselves. And that is just where the field of human embryonic stem cells stands: largely excluded from public view, but in private, a subject that is hot and getting hotter. It's only a matter of time before it bursts out from behind closed doors and begins to transform the public debate over biomedical ethics and, perhaps, much of medicine as well. TR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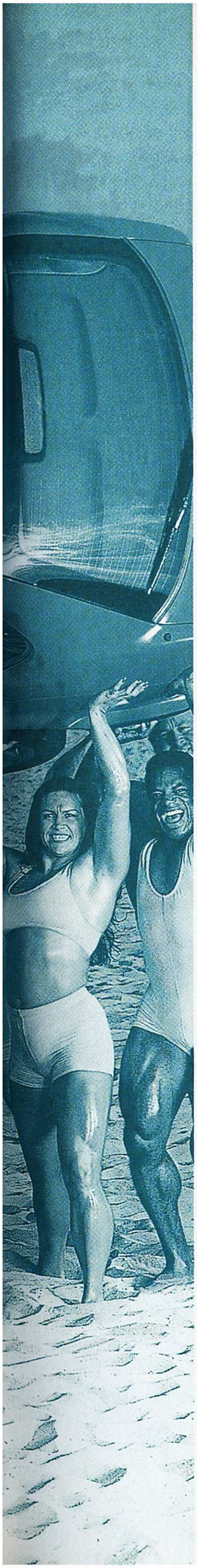
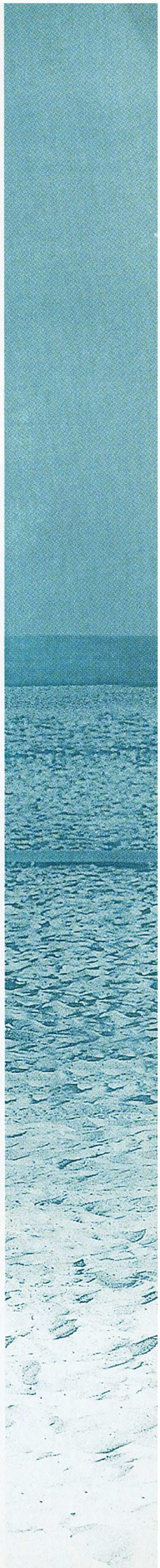




The Big, Bad Bit Stuffers of IBM

Phenomenal improvements in disk-drive capacity have brought glory to a corporate research lab that had once looked like an expensive mistake.

BY CLAIRE TRISTRAM

Bob Fontana, research member at IBM's Almaden Research Center in San Jose, Calif., is only half joking when he says Silicon Valley should have been called Iron Oxide Valley. Or even Rust Valley. Because for Fontana, it's iron oxide—the original material used to coat the disk drives that store magnetic bits of information—that fueled the growth of Silicon Valley.

Of course, he may be a little biased. IBM invented the disk drive in San Jose in 1956, when this part of the world was better known for cherry orchards than industrial parks. Since then, Almaden researchers have repeatedly smashed the record for how much data can be stored on a disk. They were up to their old tricks again last December, when Fontana and his colleagues squeezed more than 11 billion bits (gigabits) onto a single square inch of magnetic material. That more than doubled the previous record of 5 billion bits per square inch, set in the same lab only a year earlier. How much is 11 billion bits? It's roughly equivalent to 725,000 pages of double-spaced text, which would stack up higher than an 18-story building. By any measure, this was a great scientific achievement.

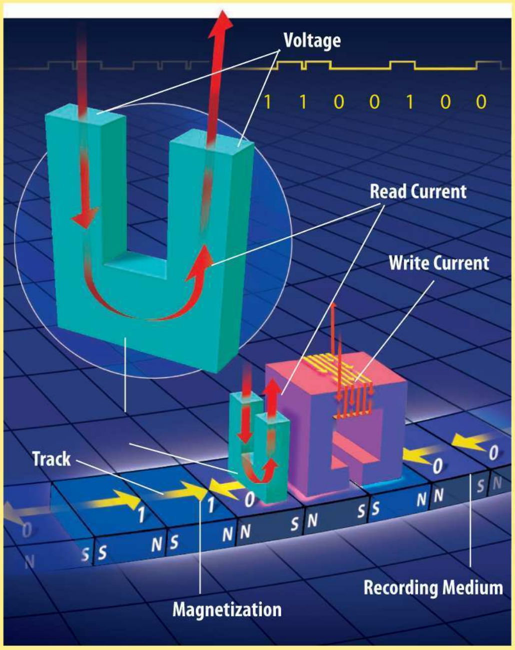
PHOTOGRAPHS BY ANNE HAMERSKY

How The Bits Are Read

Although Almaden's researchers have pushed disk-drive technology forward on a number of fronts, the lab's most dramatic breakthroughs have been in design of the reading and recording head.

As the bit density increases, the bits get smaller and the stored fields become more likely to influence the polarity of neighboring bit fields. To get around this problem, the fields must be very weak; the more closely packed the data, the weaker these fields must be. Advances in head technology have allowed disk heads to read ever-weaker, ever-smaller bit fields accurately.

The earliest drives used ferrite heads, essentially U-shaped magnets with north and south ends—impossibly bulky by today's standards. IBM's first big breakthrough was the thin-film inductive head. Thin-film heads are manufactured using a process similar to semiconductor manufacture. A substrate is coated with a thin alloy to produce a head that is much smaller than the ferrite head, able to read and write to a smaller area of the disk and to fly more rapidly over the disk surface. Changes in materials and coating techniques have allowed thin-film heads to remain in use, particularly because their manufacturing processes are cheaper than the head designs that followed.



Super sensor: A magnetoresistive head changes electrical resistance in response to a disk's magnetic field. MR devices are much more sensitive than earlier read heads.

IBM's development of the magnetoresistive (MR) head in 1989 was another major step. Unlike earlier designs, the MR head was composed of two separate technologies: a thin-film inductive write element, essentially unchanged from the previous generation, and a magnetoresistive read element, which operated independently of the write head. By having separate heads for what are very different and often conflicting operations, it is possible to optimize reading and writing operations independently.

The MR read sensor works by a different principle than earlier disk-drive head designs. In an inductive head, the magnetic fields on the disk must induce a current in the same coil of wire that is used for writing. By contrast, an MR head's separate sensor is made of a conductive material that changes its resistance in response to the magnetic field from the bits on the disk. A current flowing through the sensor produces a voltage that changes with the resistance. Because the MR sensor is more sensitive to magnetic fields than an inductive sensor, MR heads can read smaller bits that are written more closely together.

In 1988, researchers in France and Germany—for once not IBM employees—discovered independently that certain combinations of layers of magnetic and nonmagnetic materials exhibited much larger magnetoresistance than predicted. These "giant" magnetoresistive (GMR) properties were observed only at very low temperatures and when subjected to high magnetic fields. But Almaden researchers understood the significance immediately, and began working to turn the discovery into the next generation disk drive. Ten years after the first observation of giant magnetoresistance, IBM shipped a drive using GMR materials in the read head. Other vendors aren't saying when they'll follow suit.

This leapfrogging has had a dramatic effect on what personal computers can do. It is these huge capacity hard drives that have made it practical for computer users to keep large amounts of extremely sophisticated software on their machines, for example. Vast hard disks have also fostered the transformation of computing from a textual activity to one filled with pictures and sounds. What's more, the way the disk-drive project is managed highlights an effort by IBM to recouple basic research to product development in the service of innovation.

Almaden's accomplishments are by now so well accepted in the world of computing that the announcement in December of yet another new record didn't make big headlines. Even competitors shrugged. "Everyone in the audience was saying, sure, that's what we've been waiting to hear," says Gordon Knight, chief technical officer for TeraStor, a Silicon Valley startup that is championing a different kind of storage technology than IBM's. But beneath this calm surface of expectations fulfilled lies a surprising story.

Filling a Hall of Fame

The world wasn't always so nonchalant about IBM's breakthroughs. After all, magnetic storage was supposed to be dead by now, replaced by optical storage devices or some other technology. Even IBM thought so: In 1970, an IBM research scientist published a paper "proving" that the technology would never go beyond 200 megabits per square inch.

But instead of believing the company's own experts, the team at Almaden topped one predicted limit for magnetic storage after another. They discovered engineering work-arounds for what were once thought to be hard physical limits. By 1989, the Almaden lab was packing 1 gigabit per square inch. In the following years, Almaden has upped the ante, demonstrating densities of 3, 5 and now 11.6 gigabits per square inch. The market has begun to take for granted that magnetic storage capacities will double every 18 months, following roughly the same feverish pace set by the semiconductor industry. The big news will be when IBM slows down.

Talk to Currie Munce, director of storage systems and technology at Almaden, and he'll complain that magnetic storage scientists are the unsung heroes of the information age. Like everyone else at Almaden,

Evangelist in chief: Currie Munce, Almaden's head of storage systems and technology, says storage scientists are the unsung heroes of the information age.

Munce likes to evangelize about storage: "We're trying to move things mechanically over millimeter distance in milliseconds and to get them to settle within tenths of microns on track," he says. "It's great science."

A visit to one particular room at Almaden shows how far IBM has run with the technology. Hanging on one wall is a single rusty platter from the original 1956 drive—proudly displayed as a rock star might show off a platinum record. Back in 1956, IBM's disk drives were refrigerator-sized boxes that held a mere 5 megabytes, on 24 platters, each 2 feet across. Today the company ships a standard PC drive that holds more than 16 gigabytes, some 3,000 times the capacity of its original product. Put the 1956 drive and the 1998 drive side by side, though, and they look the same except for scale. Dave Thompson, director of Almaden's Advanced Magnetic Storage Recording Laboratory, says the inventors of the original disk drive could walk into his lab today and know exactly what was going on.

Storage density depends on the size of the magnetic bit: that portion of disk real estate that is given a particular magnetic orientation—north or south—to represent a binary one or zero. At the most elementary level, the goal is simple: Shrink the bits and you expand the storage capacity. But smaller bits emanate smaller magnetic fields, which in turn requires positioning the reading head—the device that senses these fields and converts them to electrical signals—closer to the spinning disk surface.

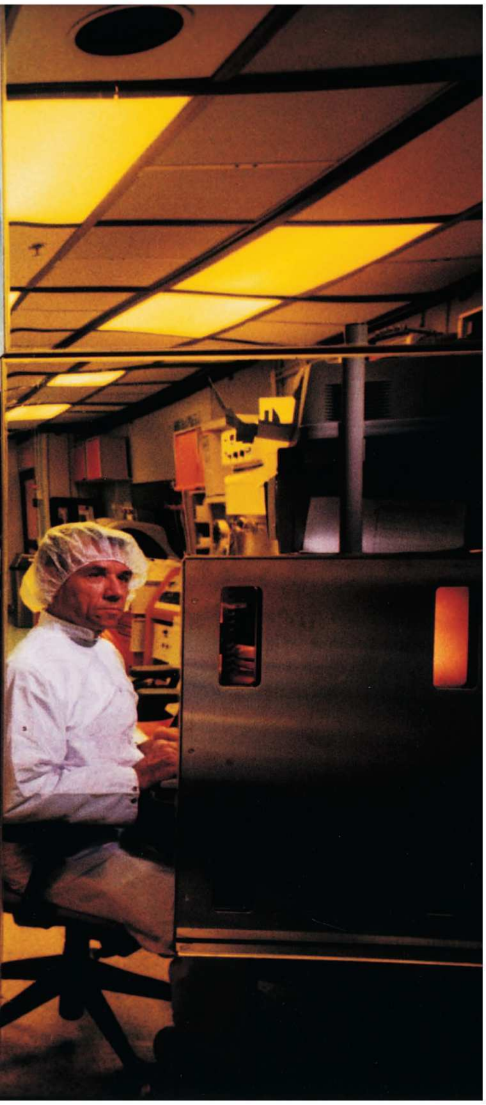
Over and over again, shrinking the technology has forced disk-drive developers to confront physical limits that first appeared to be insurmountable. For example, the head rides on a cushion of air created by the spinning disk. Conventional wisdom held that bringing the head too close to the surface would squeeze the air molecules into a space so small the supporting cushion would disappear. "There was a lot of math to back those conclusions up," says Barry Schechtman, executive director for the National Storage Industry Consortium (NSIC), an intercompany consortium of storage manufacturers that funds basic research at several universities. The happy reality, however, was that this theory was not true. "Nature turned out to be smarter than our equations, which needed to be modified," says Schechtman.

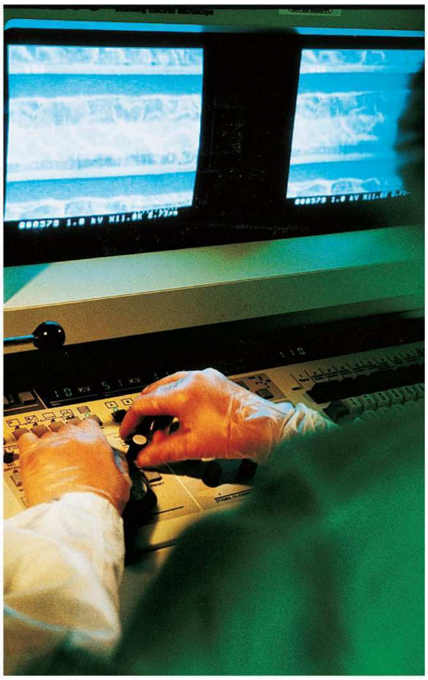
Rethinking Research

Almaden's dramatic progress in magnetic recording is all the more remarkable when you consider its institutional history. In the early 1980s, IBM's research division had a reputation for performing brilliant work that had little relevance to the company's business. And even when the labs did produce findings that had commercial implications, the handoff to product groups was often fumbled, allowing other companies to capitalize on IBM's research breakthroughs before IBM did. By 1981 IBM had fallen so out of touch with the market that Big Blue had to cobble together its first PCs out of components—including disk drives—made by other companies.

The Almaden building itself is a throwback to the great research labs of the past, surrounded by hundreds of millions of dollars worth of empty real estate, where the only sound is the wind sweeping over the Santa Teresa foothills. Conceived in the late 1970s when IBM had money to burn, Almaden was to be a showcase institution for pure research on a par with AT&T's Bell Labs, Xerox's Palo Alto Research Center, and IBM's own research facility in Yorktown Heights, N.Y. By the time the building was completed in 1985, though, the climate for

The 1-gigabit challenge was the catalyst for deep changes that brought the researchers out of their ivory tower.





Magnetic mission: Bob Fontana (far left) led the team that crammed eleven billion bits per square inch on a disk. Dave Thompson (near left), director of the Advanced Magnetic Storage Recording Lab, peers at a tiny GMR disk head. Electron micrographs reveal the structure of a GMR reading head (below).

corporate R&D had changed. New CEO John Akers—a man who liked to use words like "cost containment" and "streamlining" when describing IBM's mission—toyed with the idea of dismantling the research division altogether and dispersing its employees into various product groups.

It didn't happen. Heiner Sussner, who was then director of storage systems and technology at Almaden, knew that if the lab were to survive, something had to change. He threw down the gauntlet to his people: What would it take to prove our relevance to IBM? What would it take, say, to reach a storage density of 1 gigabit per square inch using magnetic storage media?

"It was a visionary thing," recalls the NSIC's Schechtman, who worked for Sussner at the time. "We didn't know if we could do it. We first tackled it as an intellectual challenge, but by 1986 we'd signed up to a schedule to pull it off."

For the first time, IBM's magnetic storage researchers consciously tried to solve problems faced by an existing product group. Previously, IBM's research teams had been working on esoteric storage techniques, such as magnetic bubbles, while other disk-drive manufacturers were focusing their research efforts squarely on the bottom line. The result? IBM stumbled badly, as more aggressive companies used their own research dollars for projects that went straight to improving their position in the market.

Just four years after Sussner had first put out the challenge to his people, they met it. In 1989, IBM broke through the 1-gigabit-per-square-inch barrier. The key was a technology called magnetoresistive recording (see page 46).

Sussner's challenge had accelerated the development of the magnetoresistive (MR) head. And for the first time in the history of IBM-Almaden, all storage system researchers—those working on head design, disk materials, electronics, software and mechanics—had reason to pull together toward a common goal. "We proved to the world that we had at least 10 years left of magnetic storage development," Schechtman says today, pride still ringing in his voice. "And we gained the confidence of the rest of the company to keep investing in us."

Out of the Ivory Tower

The 1-gigabit challenge was the catalyst for other deep changes that brought the research scientists at Almaden out of their ivory tower and into the real world of profits and losses. Almaden began to do regular joint development work with IBM's Storage Systems Division, the product group down the hill. Soon, one-third of Almaden's research budget was coming from the product division. Munce feels that the ratio of funding gives the research group clarity without compromising independence.

The change in funding has also created a new kind of thinking about innovation, Munce says. "Ten years ago the attitude here was: if I didn't invent it, I don't want to work on it, because I won't get credit for it," he explains. "Today we're trying to say: If you invent it in the lab, or if you're the first one to grab it out of someone else's lab and make it relevant, we don't care."

Munce holds a joint managerial position that reports to both the research and the product divisions. It was a position created in the early 1990s to make the ties between the two groups even closer. He sits in on the meetings of the product divisions and then tries to figure what research is needed to serve their missions. Putting on his research hat, his job is to influence IBM's product divisions to move in directions that take advantage of the work coming out of the labs. "My job really is to manage innovation," he says. "We need to be separate so we can innovate, create and motivate people to do good research. But we need to be connected to get technology to market."

A graphic example of how far the

research team has evolved from the original vision for Almaden is the Advanced Magnetic Recording Laboratory itself. The lab, designed by research staff member Fontana, is jointly staffed by research and product groups. Two years after Almaden first opened its doors, Fontana convinced his managers to rip the guts out of one wing on the first floor. This renovation gave him a 5,000-square-foot lab to do prototyping work—the kind of work that used to be done by IBM's product engineers instead of its research staff. This lab provides facilities for building components quickly, allowing the researchers upstairs—specialists in read heads, write heads, materials science and other areas critical to disk-drive technology—to test whether their innovations would work together.

Although Almaden has focused more on profits than on patents for several years now, these efforts have only just begun to pay off in the market. Change takes time, particularly when you're trying to alter an organization whose projects take a dozen years or more to complete. "It's only in the last couple of years that they've arrested that market share erosion," says Chris Bajorek, a former R&D executive at IBM and now chief technical officer at Komag, a leading manufacturer of thin-film disks. "Many of the products you see coming out of IBM today have had a gestation period of 10 or 20 years. They were initiated by visionaries, many of whom have since retired from the business."

Today IBM has 40 percent of the portable storage market for laptops, the fruit of 15 years of hard labor in research groups both at Almaden and at the company's Tokyo labs. Other magnetic storage projects at Almaden have had similarly long incubation periods. The MR head took 10 years from conception to product rollout in 1991. The new "giant magnetoresistive" (GMR) head, which was used in the 11.6-gigabit-per-square-inch demonstration, was a relatively minor tweak in the technology. Yet 10 years elapsed between the first laboratory observation of GMR in 1988 and the introduction by IBM earlier this year of the first commercial GMR disk drives. Few other companies, of course, can afford a decade-long lag between research investment and commercial payback.

Almaden has become more customer-focused, yes. More applied, yes. In

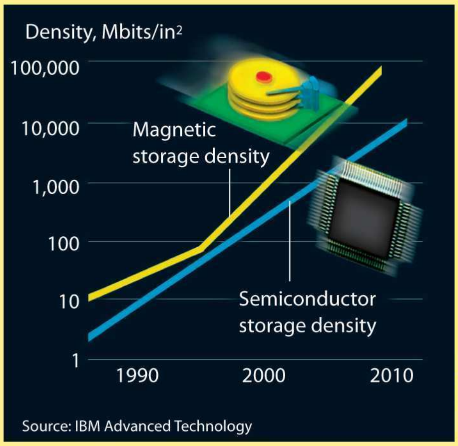
Limit, What Limit?

How long can this go on?

For the past seven years, disk drives have been upping their storage density—the number of bits per unit of disk surface area—at 60 percent a year. But every new breakthrough pushes the magnetic storage industry toward a physical limitation that no lab in the world knows how to get around. At some point, the magnetic zones representing individual ones and zeroes will become so small that they will be unstable; the slightest change in temperature could flip these bits from north to south unpredictably, turning data into mush.

Today's thinking puts this "superparamagnetic limit" at a density between 20 and 40 gigabits per square inch. At current rates of progress, that gives storage scientists only a few years of open-field running before they hit the wall.

Breaking through that limit, many experts feel, will require a fundamental shift in disk-drive technology. Market leader Seagate, for example, recently bought Quinta Corp., a San Jose, Calif., startup that is working on a combined optical and magnetic recording technique. Quinta doesn't have a product, or even a working prototype—but the mere promise of a barrier-breaking technology convinced Seagate to pay $375 million for the company.



BETSY HAYES

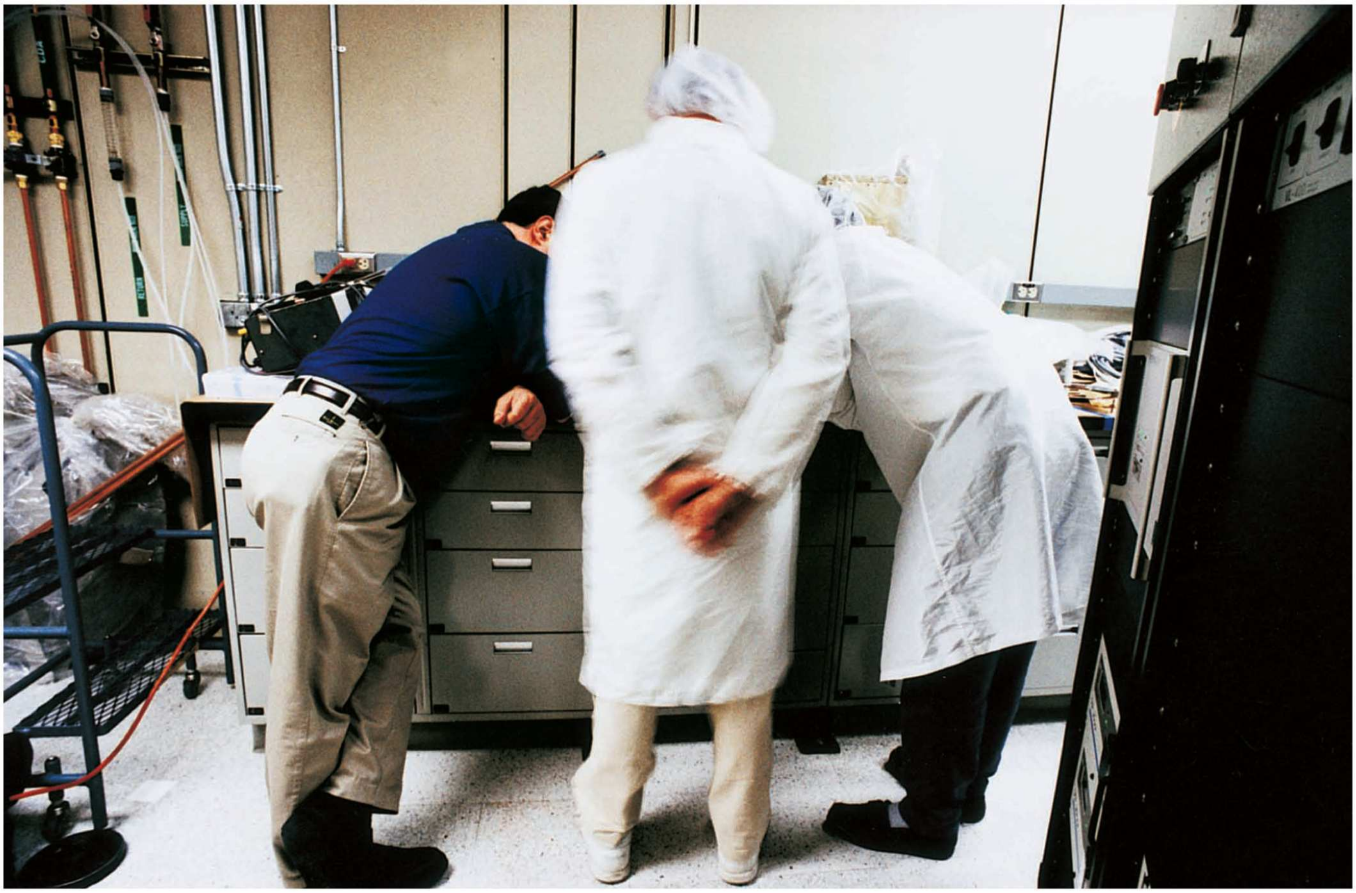
Pack it in: Advances in disk capacity outpace those in semiconductor memories, thanks to technologies developed at IBM's Almaden Labs.

Quinta's proposed disk is composed of amorphous rare-earth transition metals, which exhibit stable magnetism at room temperature—even at bit sizes much smaller than those allowed by the predicted superparamagnetic limit. To write data, tightly focused laser pulses heat spots on the disk to a temperature at which the magnetism can be changed easily without affecting neighboring bits. To read the data, a lower power laser beam illuminates the disk; light bouncing off the disk will have different polarization depending on the disk's magnetic field. No one knows if it will work; even Quinta's own press releases are sprinkled with disclaimers.

Seagate competitor Quantum Corp. is investing in a different San Jose-based startup that is also pursuing a magnetic-optical solution. Quantum is sponsoring research at TeraStor and has an exclusive licensing agreement with the company. TeraStor's key idea is to put the read/write head much closer to the disk surface than conventional drives do. The TeraStor drives will include a "solid immersion lens," a technology developed at Stanford University for which TeraStor holds exclusive patent rights. Such lenses focus laser light so tightly that the company's products, if successful, will be able to read bits four to five orders of magnitude smaller than is possible with conventional magnetic technology.

The specter of barriers to further progress is fostering an unprecedented spirit of cooperation among leading disk-drive makers. Seagate, for example, will contribute to TeraStor's research in head design. And Seagate, Quantum, IBM and eight other companies are funding a joint project to reach a storage density of 100 gigabits per square inch, using traditional magnetic media. This effort is being coordinated by the National Storage Industry Consortium, which is based at San Diego State University.

According to the principle of the superparamagnetic limit, that project is doomed to failure. But that detail doesn't appear to worry the folks at IBM's Almaden Research Center. The Almaden crew views the superparamagnetic limit as just another supposed barrier that is waiting to be broken. "We prefer the term superparamagnetic effect to superparamagnetic limit," says Currie Munce, director of storage systems and technology at Almaden: "We have 40 years of history in this business of getting around these things."



these ways the company has learned hard lessons from its competitors, none of whom has ever funded a separate research division. But IBM is still IBM, a $76 billion company with the cash to fund decades-long projects. Thus Almaden has retained technical leadership, a complicated balancing act that no other company has the resources to attempt.

Heads together: Specialists in various disk-drive elements collaborate at Almaden to make sure new technologies work together.

IBM has long been the world leader in storage R&D. Now the company has "closed the loop between research and product development," says Jim Porter, president of Disk/Trend Inc., a Mountain View, Calif.,-based market-research firm that follows the magnetic storage industry. Thanks to the targeted work at Almaden, IBM is "six to twelve months ahead of any other company" in shipping drives with the latest advances in recording technology, says Porter.

For years, magnetic storage capacities have doubled every 18 months. The big news will be when IBM slows down.

No matter how much Almaden evolves, though, it's clear that IBM will never dominate the disk-drive industry as it did in the 1950s, when it had 100 percent of the market. The long divorce between the company's research spending and its product development still has it playing catch-up, with the company running second to Seagate. And as the physics of how to cram still more data into smaller areas gets more and more complicated, it's also becoming less likely that one company will dominate magnetic storage innovations the way that IBM has in the past. Other companies are pushing competing technologies to challenge IBM's technology leadership (see page 50).

And IBM knows it. As the company has shifted its emphasis from pure to applied research, its commitment to funding pure research in joint programs with other vendors has grown. While IBM competes fiercely to achieve an advantage in the next generation, the company is cooperating with other disk-drive makers to an unprecedented degree in the fundamental science that will allow for breakthroughs three, four or more product generations from now.

"In 1982 if you looked at the research dollars going into magnetic recording, IBM dominated," says storage technology director Munce. "Today, we don't dominate. There's a lot of great work out there, and it would be very arrogant to think we could invent everything ourselves."

Munce pauses. You can almost hear him thinking: Wait a minute, we *have* invented everything ourselves. ◊

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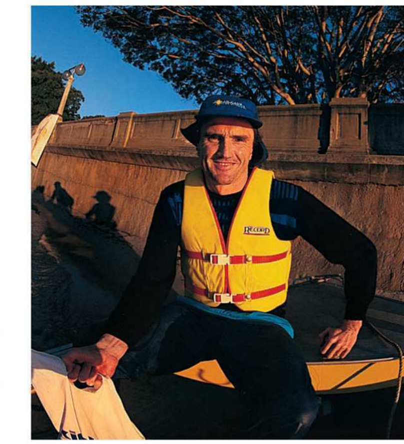
Winging it: Grame "Butch" Johnson (left) and Bruce Heggie (right) sail a prototype solar craft on Sydney Harbor. On the next page is the boat's inventor, Robert Dane.

This strange new boat sails on gusts of wind, rays of light and the passion of a novice inventor from Down Under.

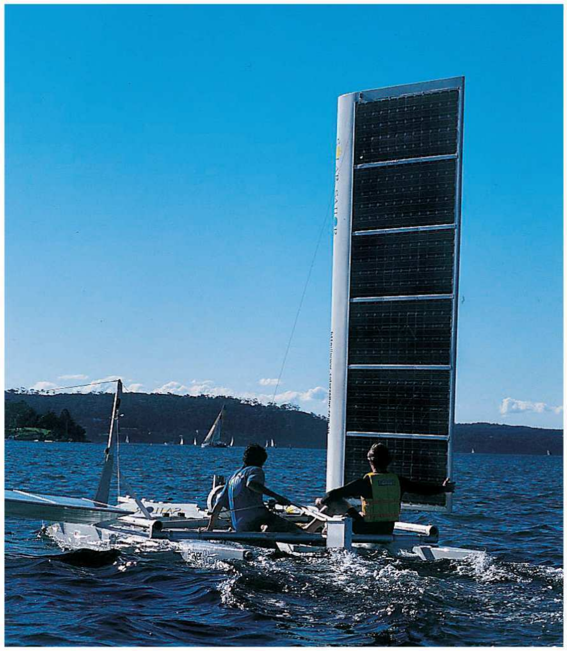


Australia's Solar Sailor

BY DANIEL DROLLETTE

SKIMMING ACROSS A MAN-MADE lake 300 kilometers southwest of Sydney, the twin-hulled *Marjorie K* looked like an exotic, overgrown waterbug. The resemblance grew as her crew manipulated the 7-meter boat's "wings"—long, broad, lightweight modules covered with waterproofed solar cells. Each cell generated electricity just as a solar cell in an everyday pocket calculator does; by adjusting the wings' angle to the sun, the crew gathered more energy for their craft's electric motor.

PHOTOGRAPHS BY TONY KARACSONYI



Pulley Power: A simple lever-and-pulley system allows each of the *Marjorie K*'s wings to move independently. Her team of sponsors, on the other hand, always pulls together.

But these wings weren't just solar collectors. Raised perpendicular to the water, they caught the breeze like a sail, allowing the catamaran to use the combined power of sun and wind to leave competitors behind at the 1997 Second International Solar and Advanced Technology Boat Race in Canberra, Australia's capital. As the boat's lead widened, however, the wind died down and the *Marjorie K* was forced to rely solely on its solar cells and batteries. The boat's support team was nervous—it was the first trial under race conditions. But to spectators on the shore, the *Marjorie K* appeared to pick up the pace.

A couple of human, rather than technological, errors earned the *Marjorie K* an extra lap and cost her first place at the finish line. (The captain was penalized for tacking too close to a race buoy and banging into another boat.) But despite these glitches, the *Marjorie K*—one of more than 40 participants in the all-solar regatta—won the $10,000 prize for Most Innovative Vessel (currently worth about $6,300 US). David Gaul, one of the race's judges, was impressed with the boat's unusual combination of wind and solar power. "The movable wing design allows you to do two things simultaneously: take advantage of the wind, and get the absolute best alignment of the panels to the sun. Just look at her," he adds. "She's easily the most innovative boat. You don't see too many *Marjorie K*s running around the world."

If this unusual vessel's inventor has his way, however, that will soon change. The *Marjorie K* is the contrivance, passion and obsession of Australian physician Robert Dane—she is also the prototype for a fleet of "Solar Sailors" Dane hopes to build. He envisions a number of incarnations of the environmentally friendly vessel: ferries and sightseeing boats for busy urban rivers and harbors, pleasure cruisers for ecologically fragile reefs and bays. By combining new designs, off-the-shelf technologies and cutting-edge research from labs Down Under, Dane hopes to have his first commercial Solar Sailor afloat in Sydney Harbor in time to ferry tourists during the 2000 Olympics.

Sun Worship

UNLIKE MOST OLYMPIC ASPIRANTS, Dane hasn't been training all his life for his moment of glory in Sydney. Far from it. At 39, he has no formal education in engineering or boat design, and until a couple of years ago he was the local doctor in the coastal village of Ulladulla, 230 kilometers south of Sydney. But Dane's imagination has been captivated since childhood by the idea of siphoning electricity from the sun's rays. He first glimpsed a solar cell in a magazine article about the National Aeronautics and Space Administration's space satellites. "I was fascinated," he recalls. "The idea of solar panels was absolutely miraculous. I became obsessed." Today, almost all conversations with him inevitably double back to the subject of solar power.

Dane has even found inspiration in his biomedical training and practice. He based his design for the hinge-and-pivot mechanism of the boat's wings, for example, on his observations of the human shoulder. The idea of solar-paneled wings hatched when Dane learned the evolutionary theory that insects' wings evolved from solar collectors. And his years in medical school at Sydney University primed him to see the advantage of coupling wind and solar energy. A longtime sailor and windsurfer, Dane knew that even a small increase in wind speed can dramatically increase a boat's energy. Like a car speeding down the interstate, a boat creates its own breeze. Proper positioning of the sails can add this so-called "relative wind" to the true wind and boost the sailing speed. Growing weary of the late hours of a country doctor, Dane began to dream of building a sailboat equipped with a solar-powered electric motor that would create more relative wind. "From med school, I knew that anytime you see that kind of positive feedback loop in nature, you should take advantage of it," he explains.

The idea is an old one. Early steamboats operated under a combination of two power sources—wind and steam—but both were seldom operated at the same time. "People do motor sail," Dane notes, "but sailboat owners generally don't like the smell, noise or pollution caused by a fossil fuel engine. They call them 'stinkboats.'" A sailboat with an electric engine, he reasoned, would provide the best of both worlds.

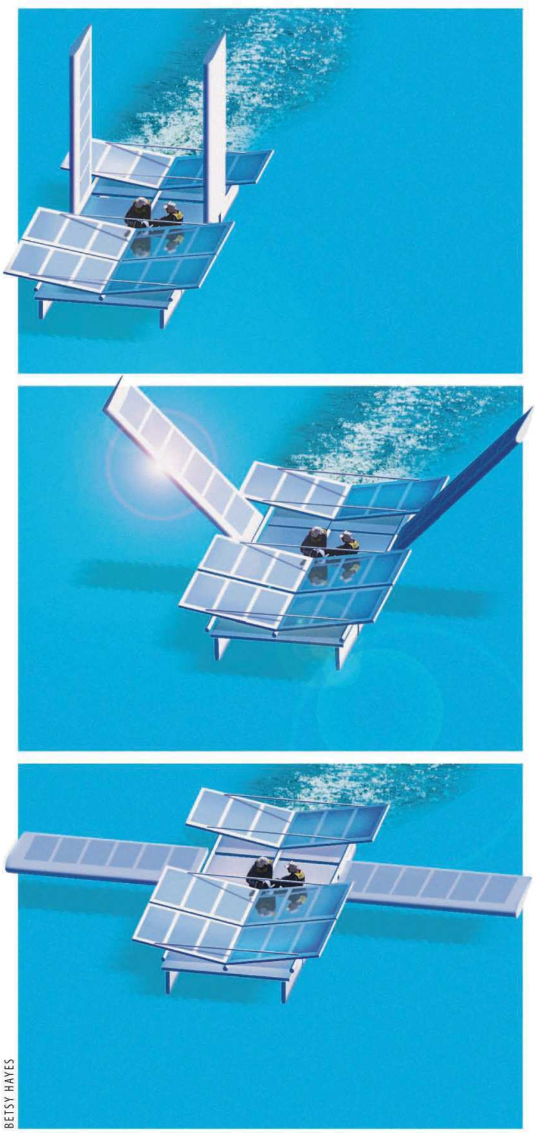
His interest spurred along by watching the first International Solar and Advanced Technology Boat Race in 1996, Dane sketched out a design for a wing that would serve both as solar collector and sail. He built a model of the key joint mechanism from pipe cleaners and his child's Lego blocks, then showed it to some boat builders at Iain Murray & Associates, a leading Sydney-based competitive yacht design firm. As he recalls with studied casualness, "I went down there with beer in hand and said, 'What do you think?'"

The designers' response was cautiously positive. They made some calculations and said the idea was feasible, so Dane wrote up a 35-page prospectus and started to raise money for the project. Ulladulla local Marjorie Kendall, a farmer and fellow solar enthusiast, was so impressed that she invested half of the $130,000 cost of a prototype boat. With the money from Kendall in hand, Dane quit his medical practice and enlisted a diverse crew of friends and neighbors that included a surfboard maker, a model-train hobbyist and a champion sailboat captain. Together, they built the *Marjorie K* in only 82 days.

The EV of the Sea

THE *MARJORIE K*'S DRAMATIC APPEARANCE last April at the Second International Solar and Advanced Technology Boat Race fit well with the race organizers' intention to raise the profile of solar power. Solar-powered boats in particular tend to be ignored, says race adviser Hans Tholstrup. When people think of vehicles powered by solar, or photovoltaic (PV) cells, they focus on cars, Tholstrup says. "The reason is that we see cars as a necessity in life," he explains. "We use them to get to work or to the shop. We're a car culture." Tholstrup, a self-described "futurist and adventurer" cheerfully admits to this bias himself; a former race-car driver, he drove the first solar-powered car across Australia in 1982. But propelling a boat with solar energy is in many ways easier than using solar energy to power a car, he says. Boats don't have to deal with hills, the energy-draining stops and starts of traffic, or the shade cast by trees and buildings. "In addition," he notes, "a pleasure boat lies idle all week long, when it could be absorbing power. You would have well and truly fully charged batteries."

Others also believe PV cells to be well-suited to use on boats. David Roche, special projects manager at the University of New South Wales' Photovoltaics Special Research Centre (PSRC), points out that boats operate at lower speeds than cars and, when outfitted with properly designed hulls, consume little energy. "You can do a lot with just eight square meters of solar panel, which you can easily get with most small craft," Roche remarks. But that doesn't mean there aren't significant engineering challenges left. "The biggest obstacles are developing an efficient, cost-competitive cell and storing what you've generated" in batteries, he says. Roche notes that though the price of PV cells has dropped from thousands of dollars per watt a few decades ago to $4 per watt today, they still cannot compete with conventional electrical power, which costs one-quarter to one-half that much. He expects the PV industry needs at least another decade to compete with tra-

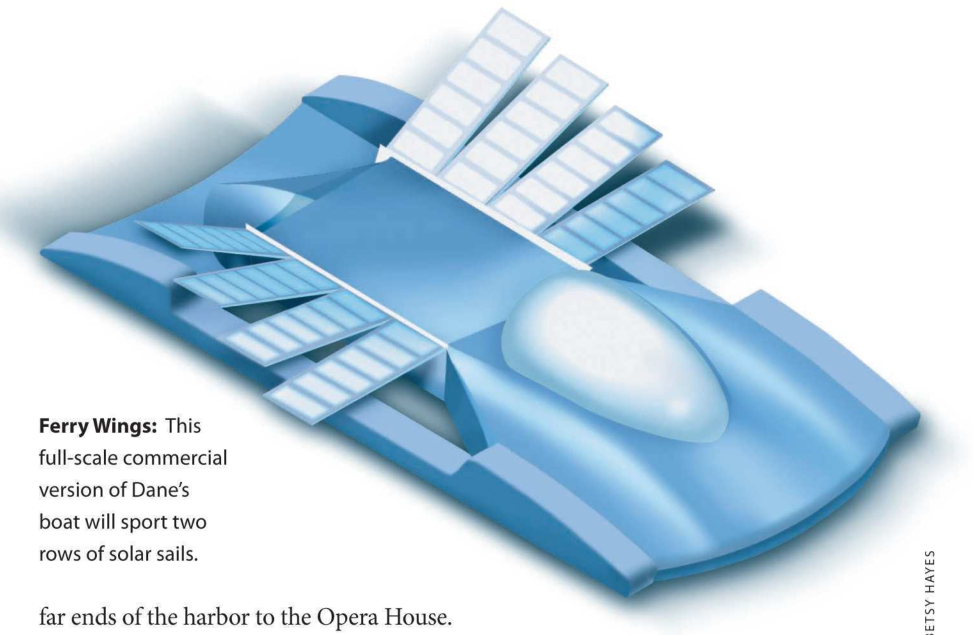


BETSY HAYES

Range of Motion: The solar wings go up for sailing (top), down for motoring (bottom) and in between for a bit of both—Dane calls it "flying" (center).

ditional power sources.

On this subject, Dane is optimistic. "The silicon wafers used now in photovoltaics are in the same position that silicon chips were for computers 20 years ago," he says. "The price is coming down, and the power is going up." What's more, Dane says, the enormous load of batteries required by an electric vehicle—the greatest drawback to a solar-powered car—can be a bonus for an electric boat. "You need tons of lead in the keel anyhow, so just put batteries in there instead," he suggests. "What's a burden for a car is ballast for a boat."



Ferry Wings: This full-scale commercial version of Dane's boat will sport two rows of solar sails.

BETSY HAYES

Setting Course for Sydney

With the Marjorie K as dramatic proof of solar sailing's principles, Dane is gearing up for the first commercial application of his inventive designs at the Sydney Olympics. Sydney, he explains, won the chance to host the Olympics largely because the city promised to stage an environmentally friendly event, the "Green Games." Dane can picture no more fitting emblem of the Green Games theme than a full-scale Solar Sailor plying Sydney Harbor.

If everything works out as Dane plans, millions of tourists will capture a strange sight in their snapshots of the Green Games: a 35-meter catamaran ferry riding low in the water with two rows of solar-cell-encrusted wings spreading out above the deck. Many of those sightseers will also have shots from the boat itself; the ferry will carry 220 people at a time on the half-hour voyage from the far ends of the harbor to the Opera House.

To recruit a designer for the Sydney Solar Sailor, Dane brought a video of the *Marjorie K* in action to Grahame Parker, a prominent boat builder with experience designing ferries for the harbor. Parker was excited by Dane's unconventional ideas. "Part of the attraction is that no one's quite done this before," he explains. Parker thinks that a larger commercial version of the *Marjorie K* prototype will need long, thin, sharp-ended hulls to slice through the water with minimal resistance, much as rowing sculls do. He also plans to lighten the full-scale version's weight by building it with carbon/epoxy or Kevlar fibers. "Even so," he adds, "the hulls are not that radical, the power source is." To hedge their bets, Dane and Parker will equip the ferry with a backup power system that runs on a fuel such as natural gas or liquid propane.

Dane predicts that building a Sydney Solar Sailor will cost $1.5 million, about the same price as a traditional ferry of equivalent size that currently serves Sydney Harbor. But operating the Solar Sailor will cost only 20 percent of what it costs to run a comparable fossil-fuel-powered ferry, Parker estimates. Dane is looking to cut a deal with an Australian cruise company that would buy the ferry and operate it at the Olympics.

As he looks forward to what he hopes will be his boat's big moment in Sydney, Dane continues to seek out other opportunities to spread the Solar Sailor vision. "It's not about me," he says. "I just want to make incredible boats. It's a passion, a point of no return." Dane wants to license his patents on the Solar Sailor wings to boat builders overseas, who would, in turn, stock the world's waterways with a strange new species of aquatic Australian insect. ◊

Superior Solar Cells

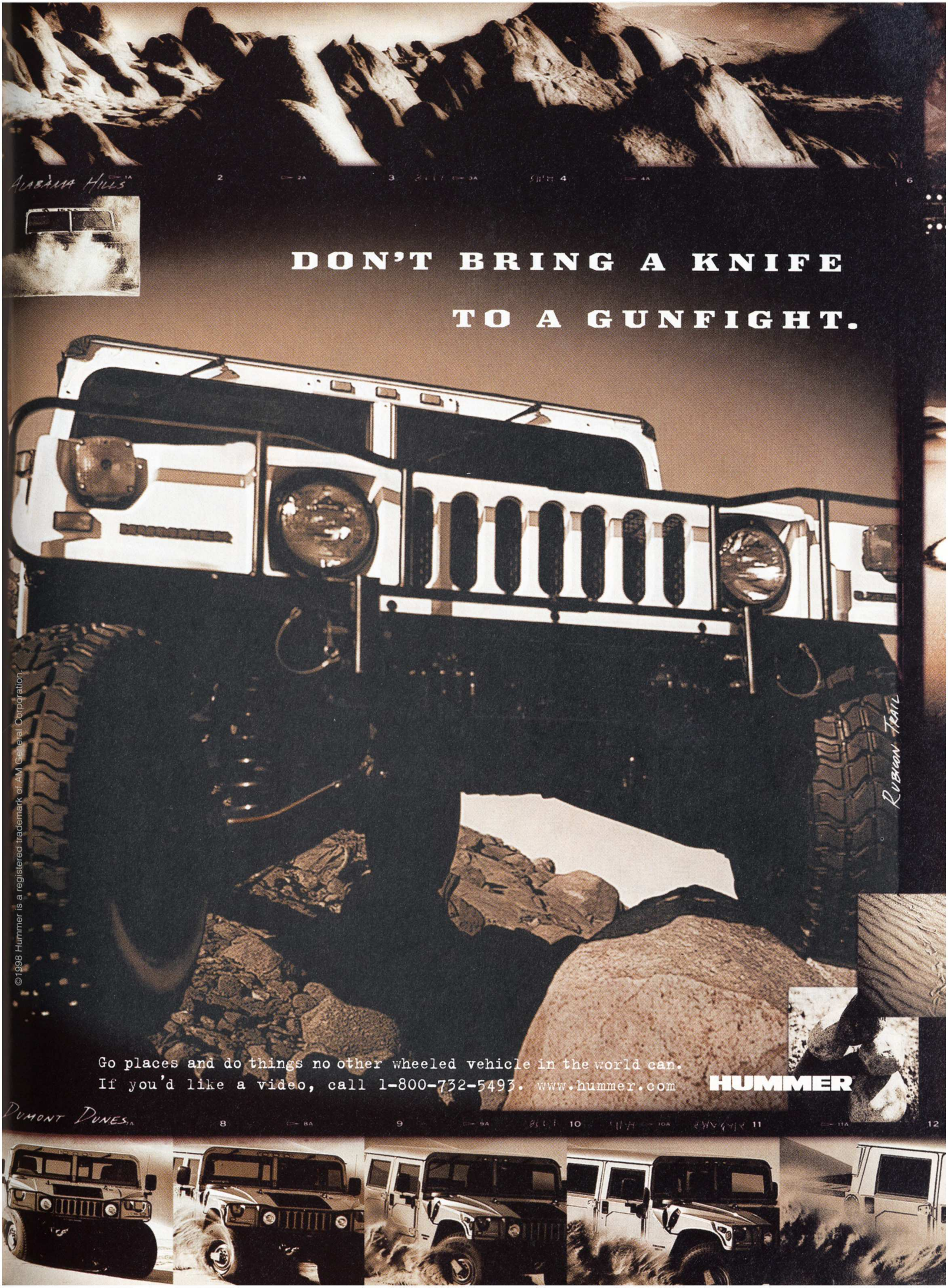
With a design in place and a deal in the works, Robert Dane figures he is close to making the Solar Sailor viable. But what he'd really like is to get his hands on the latest PV cells coming out of the lab at the PSRC. Australia has long been a leader in the development of solar energy, motivated in part by the huge expense of stringing long-distance power lines across a sparsely-settled, vast continent. For the past 15 years, the PSRC has developed cells with some of the highest efficiencies in the world.

PV cells consist of two very thin layers of light-sensitive material. The lower layer easily loses electrons while the upper layer easily gains them. When a photon of light strikes this sandwich, it dislodges electrons from the lower layer and into the upper, creating an electric potential between the two. This potential provides the electric current through the rest of the circuit.

To conduct the current, most cells have fingers of metal on the surface. But these fingers block some photons out of the light-sensitive areas. So PSRC researchers recently created a cell with electrical contacts in the middle, instead of on the surface. "The advantage of this is that you get 25 percent more power for the same cost of production," says the project's manager, Christiana Honsberg.

Researchers at PSRC are also working on a "bifacial cell" that absorbs light from both the top and the underside of the cell. (Traditional PV cells have a light-absorbing layer just on one side.) With a bifacial cell, light that is currently lost—such as that reflected off the earth or water—could be absorbed as well.

The PSRC has been a resource for Dane, advising him on techniques for wiring PV cells together and keeping them glued to his boat. The center will give Dane first crack at the latest generation of highly efficient PV cells as soon as they come to market, probably some time in 1999.



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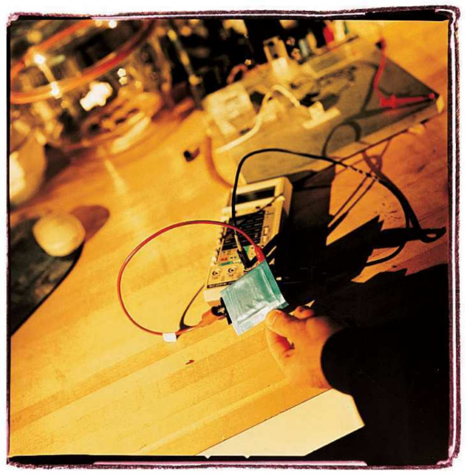
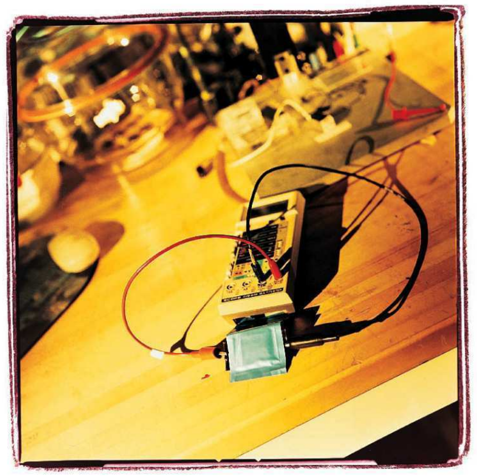




and **waiting** to **go**

BY AMY SALZHAUER

Many people check their fax machines every morning, but these days Theodore Poehler and Peter Searson are taking a particular interest in what appears on theirs. This pair of Johns Hopkins University scientists believe they are achingly close to a deal that could turn their research brainchild—an all-plastic battery—into a commercial reality. Each day they expect to see the final outcome of more than a year of negotiations, hoping for a decision from several large battery companies or word from private investors who have expressed a willingness to put up tens of millions of dollars.

An agreement with the right battery company or group of backers could transform their invention from a laboratory curiosity into a rising star in the huge battery market. The prototype is remarkable—small, light and rechargeable. Even more intriguing, it comes in thin, bendable sheets that can be formed into a shape resembling a business card. Poehler and Searson think the novel battery could play a leading role in a new generation of electric vehicles, satellites and lightweight electronic devices—even as a replacement for standard AA-size batteries.

PHOTOGRAPHS BY CHRIS HARTLOVE

Charging it up: Johns Hopkins scientists (from left to right) Jennifer Giaccai, Peter Searson, Jeffrey Killian and Theodore Poehler are still working to optimize the plastic battery.

That's the dream. Making it a reality, though, takes money—lots of money. It also takes business savvy. And Poehler and Searson know there's no guarantee of success. "We are both very guarded," Peohler explains. "If it happens, it happens—if it doesn't, well, we are trying to just think about doing the research to make the technology better."

Their story is a tale of how basic researchers working on the cutting edge can find themselves in the world of entrepreneurship, venture capital and big business. And how, once they get there, the issues may be just as complex—and far less familiar—than those they face at the lab bench.

Poehler, a professor of electrical and computer engineering and the university's vice provost for research, and Searson, a professor of materials sciences and engineering, never set out to be entrepreneurs. When they began their search six years ago for an all-plastic battery, they just wanted to do good science, testing the limits of a material and a system. The professors headed a team of researchers at Johns Hopkins that included Jeffrey Killian, Josef Gofer and Haripada Sarker; graduate student Jennifer Giaccai subsequently joined the group. Progress came slowly, but by 1996 they had a workable prototype. Then, early last year, a Johns Hopkins University press release touting the development of the novel plastic battery triggered a media frenzy.

The plastic battery was named "Invention of the Year" by *Popular Science*. TV crews arrived from as far away as Sweden, Tokyo and Brazil and roamed the lab. The researchers appeared on

CNN and in *USA Today*. Graduate students in the group became local media stars. Hundreds of companies and investors inquired about the new technology, trying to turn its electrical potential into earnings potential. Wall Street analysts called to get the scoop on any deals that might be signed to produce the battery commercially.

These days, more than a year later, the lab is just about back to normal. A recent visit by *TR* found the usual hush of a university lab, the researchers going about the business of doing science. The TV crews are gone. The steady stream of visitors thinned.

Out of the glare of the media, the Johns Hopkins team, like other academic researchers who have developed a hot new materials technology, is navigating the world of business and finance.

Make no mistake—the stakes are high. Successful commercialization of a plastic battery could mean big bucks for its academic inventors and their university. The U.S. market alone for batteries is $5.8 billion a year and is poised for rapid growth as a new generation of electric vehicles and smaller electronic devices drives a need for more efficient, lighter rechargeable batteries. Corporate and academic labs around the world are racing to find the solution, with many efforts focusing on lithium-based batteries (see page 65).

A plastic battery could carve out a lucrative niche. Most batteries today are made of toxic and environmentally damaging heavy metals such as lead and cadmium. Plastic batteries, however, contain no metals and are easily recycled. They must be sealed so that moisture doesn't dampen their charge, but the polymers inside are a far cry from lithium, which can explode when exposed to water.

What's more, the all-plastic battery is made of thin, foil-like sheets—a critical advantage for someone designing a product who needs to figure out where to squeeze in a battery. Imagine casings for laptop computers lined with thin sheets of the battery or car structural parts that are lined with the power sources, even satellites where the plastic battery is crammed into any available space. "You can make it into just about whatever configuration you want," says Searson.

Despite those payoffs, plastic batteries have never made it to the marketplace. Plastics are cheap and easy to use, but normally they are insulators—the opposite of the conducting materials required for batteries. Plastics are good for wrapping wires, but few thought of them as the stuff of batteries.

Then, in the late 1970s, a chemist at the University of Pennsylvania made a startling discovery that jump-started the whole field. Alan MacDiarmid found that he could make the polymer polyacetylene into an electrical conductor by "doping" it with the right set of ingredients. The discovery completely changed how chemists thought about plastics. Suddenly the whole world of electricity was a possible new terrain for the materials. MacDiarmid himself tinkered with making plastic batteries in the lab. But the devices remained a laboratory curiosity.

A laboratory oddity, perhaps, but an intriguing one. Battery labs around the world began exploring conducting polymers. Yet when they did, they ran into the same obstacle. While it was relatively easy to find a polymer that could act as a cathode (the positive terminal of a battery), it proved difficult to make a polymer serve as an anode (the negative terminal). Most labs effectively gave up on the all-plastics idea, compromising on batteries with a polymer cathode but a metal anode, using, say, lithium.

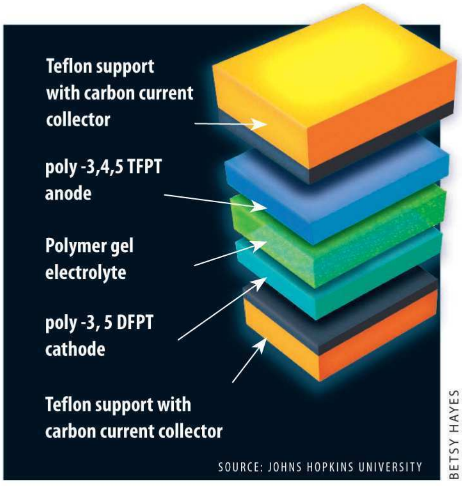
The **right** deal could mean a **lucrative** pay day. The **wrong** one could mean the plastic battery may **never** emerge from the **lab.**

Then, six years ago, scientists at the U.S. Air Force's Rome Laboratory asked the Johns Hopkins group whether it could make an all-polymer battery for defense and aerospace applications. A plastic battery, the reasoning went, would be invisible to the detection devices that easily pick up metal-based batteries. Searson and Poehler had no idea whether the concept would work. "We were wondering whether you could make a reasonable polymer battery at all," remembers Poehler. "It was a big question, and it was not obvious whether the answer was yes."

Although the execution was complex, the concept behind the plastic battery idea is simple. "All batteries use the same basic components—an anode, a cathode and an electrolyte—to convert chemical energy to electrical energy," explains Poehler. The two electrodes, the anode and the cathode, act as surfaces where electrons can be exchanged. The anode is made of a substance that readily gives up electrons—usually a metal like lead or lithium. The cathode, in turn, must be able to accept electrons. The idea of a plastic battery is to simply replace the metals with electrically conducting polymers.

The trick is finding a polymer anode suitable for a workable battery. When used in a battery, certain polymers can act as great cathodes, readily accepting electrons coming from the anode through an external circuit. On the other hand, for a conducting polymer to act as an anode, it must be doped so that an extra electron is forced into the polymer backbone, giving it a negative charge. Unlike doped cathodes, however, doped anodes are unstable and vulnerable to moisture.

Despite the challenge, the Johns Hopkins team charged ahead. Eventually they found that by entrapping a lithium ion in the polymer chain they could make a type of plastic called polypyrrole behave as an anode. After three years of effort, Poehler felt that this system "started to look decent." By the summer of 1995, the lab produced a



Plastic sandwich: The battery uses two types of polymers, one as the cathode and one as the anode. A plastic gel is the electrolyte.

working battery. But the battery produced only about one volt per cell—far too low for many applications—and it still required lithium as a dopant.

The team went back to the drawing board. This time they made a significant breakthrough in a little more than six months. The Johns Hopkins team turned to a family of polymers called fluorophenylthiophenes to form the electrodes; one member of the family, 3,4,5 TFPT, acts as the anode, while another, 3,5 DFPT, as the cathode. The polymers were then sandwiched around a battery electrolyte made from a thin polyacylonitrile gel. The battery could produce three volts of electricity per cell and be recharged hundreds of times.

It was a remarkable breakthrough. The batteries are as flexible as plastic wrap—so they can be rolled into the cylindrical shape of a conventional flashlight battery, or used as credit-card-thin sheets. Unlike conventional batteries, which often do not work at temperatures much below freezing, they are capable of working at temperatures as low as -40 degrees C. As an extra bonus, the batteries change colors when they discharge, making it easy to tell when a recharge is needed.

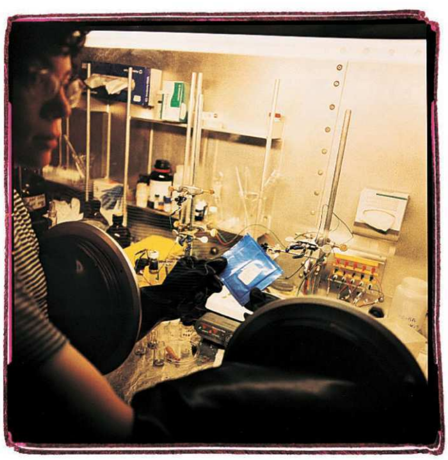
Now the lab had a workable prototype, but it was only the starting point on the hard road to commercialization. Poehler, who has seen lots of technology transfer deals in his capacity as vice provost, took the lead in the team's business effort. "The first challenge is to determine if the technology is competitive," he explains. By late 1996, when the story broke in the media, the Johns Hopkins researchers were confident that their battery had reached that stage. They sorted through the deluge of requests and met with more than 40 potential research partners or funders, going on visits or being visited by companies or research groups almost every week for more than a year.

"We did not look at most of the meetings as opportunities to do business deals, but as chances to exchange information," Poehler says. Yet the overarching goal was to make a major deal that would bring the battery to the market, not just bring in money to do further research. "We are still working on this, and are always struggling to get to the point where the technology sells itself," he says.

Getting to that point, however, isn't easy. In fact, it means negotiating a complex world of venture capital and corporate financing. Poehler and Searson each have impressive academic reputations, but, like most scientists, neither has much experience in business wheeling and dealing and the world of high finance.

"It requires a different skill set than science," says Lita Nelsen, director of MIT's Technology Licensing Office. "There are a few people who have both skill sets, but not many." The increasing supply of venture capital dollars and corporate investors looking for hot technologies means growing business opportunities for university scientists. Nelsen says, however, that scientists frequently focus exclusively on the financial aspects of a deal when "they actually should be looking for more than money. Money is available. They should be looking for wisdom that goes along with it—wisdom to know what to do in judgment situations like when the chief executive isn't working out, or when someone is infringing on their patent."

Academic researchers face a number of difficult decisions, as they try to guide



Manipulating polymers: Giaccai (top and left) fine-tunes the battery, which is enclosed in a glove box to protect it from moisture. The polymer 3,4,5 TFPT proves itself as an anode (right).

Electric vehicles drive **battery** innovation

The plastic battery invented at Johns Hopkins University has some impressive credentials. But, as it attempts to graduate from the lab and to the marketplace, it's going to find that it's just one more player in the highly competitive scramble to commercialize the next generation of battery technology.

A major prize is the anticipated boom in battery-powered electric vehicles. And it's a race that's drawing some of the world's largest—and most technologically savvy—corporations. "Everyone wants to be in the electric vehicle business because it's so huge," says Christina Lampe-Onnerud, a battery scientist at New Jersey-based Bellcore.

Those in the battery business may be salivating at the opportunities, but picking the right technologies from the mix of high-tech and low-tech options is tricky. Battery plants require tremendous capital investment, so manufacturers naturally want to feel confident before they bet on a particular technology. At the same time, there's pressure to get into the market quickly. "The real pay-off [for any battery technology] is in being first to the market," explains one Wall Street technology analyst. These countervailing pressures have researchers and battery makers thinking long and hard about the new technologies that are in the pipeline and comparing them with the available low-tech solutions.

One possibility comes from the electronics industry: lithium-ion batteries. Although these newcomers are set to revolutionize some aspects of consumer electronics, many observers doubt that the batteries will ever make it into cars. The automotive industry is fanatical about safety, and lithium is highly reactive and can ignite stubborn fires. In addition,

FORD MOTOR CO.

Electric pickup: Ford's 1998 Ranger uses a 2000-pound lead-acid battery for power.

the current generation of lithium-based batteries usually uses cobalt, a relatively expensive metal.

Market pressures, however, have led to some innovations in the lithium-based approach that might overcome these problems. Bellcore has begun prototype production of a lithium-ion polymer battery that is lightweight and flexible; most important, it's engineered to be safer than the earlier generation of lithium-ion batteries. "When we designed it, we aimed to find the technology that could store the most energy in the smallest space with the least weight and at the lowest cost—but we insisted that safety should overrule everything," says Lampe-Onnerud.

Another of the current leaders in the race is a lithium-polymer product that is being commercialized jointly by 3M and Hydro-Quebec. These partners say that theirs is the first solid-state battery for electric vehicles. Unlike the lithium-ion batteries, which have a liquid electrolyte, the 3M-Hydro-Quebec battery is dry; a thin sheet of conducting plastic serves as an electrolyte. The group says the use of a polymer electrolyte allows for safer use of lithium.

The winning battery technology, however, might not be any of these commercial contenders but one that's still on the lab bench. One candidate is a lithium-polymer battery created at MIT by a team of materials scientists including Donald Sadoway, Yet-Ming Chiang, Gerbrand Ceder and Anne M. Mayes. They designed a battery that replaces most of the cobalt with a far lighter and cheaper metal, aluminum. In addition, the MIT scientists use a novel block copolymer (a combination of two different polymers bonded together) to act as the electrolyte.

Their prototype is light, powerful and flexible. And while it will probably find its initial uses in electronic devices, Sadoway says the ultimate goal is clear. "If this thing works, it could be the link that could herald the dawn of an electric vehicle age."

But those who are actually going to be picking the winners may take some convincing. Take John Wallace, director of the Alternative Fuel Vehicles Program at the Ford Motor Co. The car maker has spent hundreds of millions of dollars on R&D for batteries for electrical vehicles, and Wallace will help to select the technology Ford uses. While he acknowledges that there are lots of interesting technologies out there, he says the clear favorite is a relatively low-tech player—nickel-metal hydride batteries.

"The labs pooh-pooh it, but for electric vehicles it will be nickel-metal hydride batteries," says Wallace. Even though they may need to be recharged more frequently than lithium batteries and require expensive materials? Even though in many applications they have been losing market share to lighter lithium-ion batteries? Yes, says Wallace. He points out that nickel-metal hydride batteries "are durable, reliable, tolerate abuse," and, he adds, what's even more important for the average driver: "The damn things don't break."

their technologies out of the lab into the business world. They could, for example, simply license their patent and move on with their research. Alternatively, they could enter into a collaboration with a company that could provide the marketing and manufacturing experience the scientists lack. Finally, they could try and find funding for a startup company of their own.

Each option has pros and cons. Whatever their decision, Poehler and Searson say they plan to stay at their academic jobs and let businessmen run any company. Licensing the technology to an established battery company is a safe bet financially but usually means giving up total control. Taking venture capital funding also might mean that the researchers would give up more control of a battery spinoff than they would have to with other private sources of capital.

At stake in the decision is whether the plastic battery ever sees its way out of the lab and emerges as a practical device. Commercializing new types of batteries is a notoriously expensive process, requiring new manufacturing plants and a long-term commitment

Still at the lab bench: While the spotlight is off Giaccai and the other lab workers (left), Searson, Poehler and Killian (right) wait for the deal that could make the battery commercial.

to a particular type of technology. Once a corporation licenses a technology, they largely gain control over its fate—including the choice to kill its development. Choose the wrong partner and the battery—once the darling of 30-second TV sound bites—can be quickly relegated to a corporation's pile of "better batteries" that never panned out.

On the other hand, the right business maneuvering could provide a lucrative payday to Searson and Poehler, as well as to a handful of their lab co-workers. Like most researchers who discover something with commercial potential, Searson, Poehler and their colleagues were careful to file a patent before they publicly released any of the findings. The university owns the patent, but profits or license fees are split so that one-third goes to the university, one-third to the researchers and one-third to the lab for its future research. If the numbers involved become very large, the researchers' personal share declines to roughly 15 percent.

Imagine lining computer casings with **thin** sheets of a battery, or a **device** with the battery **crammed** into any available space.

For the moment, however, the Johns Hopkins plastic battery seems to be hung up on a Catch-22 that frequently plagues labs looking to market technology in early development; the project needs more funding to reach the next stage of development but the financial backers want to see more highly developed technology before they will loosen the purse strings.

What's more, while the venture capital market continues to boom and is a ready source of dollars for startups in information technology and biotech, venture investment in new materials remains a sluggish—often neglected—sector. "Wall Street doesn't like materials stories," says Joe Lovett, a general partner of Medical Science Partners, a venture capital firm in Wellesley, Mass., which finances both biotech and materials science startups.

Josh Lerner, an associate professor at Harvard Business School and expert on venture capital, says, "Materials science had a brief surge of popularity in the late 1980s with high-temperature superconductivity. But people seem to have become disillusioned with the area." Lerner says that even with the boom in venture investment, "there is still a very narrow band of technologies that are funded; 80 to 85 percent of the companies are in information technology and the life sciences."

Beyond such funding obstacles, the plastic battery faces tough competition from several other promising types of batteries, including zinc-air batteries and lithium batteries. Each of those technologies has hundreds of millions of dollars of investment and a critical headstart. Some have already been manufactured on a large scale. Like the plastic battery, they're efficient, lightweight and compact. Lithium-polymer batteries, for one, can be molded into almost any shape, even cut into pieces without losing their charge.

So what are the odds that one day we'll find ourselves riding in cars with parts lined with plastic batteries, talking on cell phones powered by the stuff? It is still too early to tell. If Poehler had his choice, "one of the world's biggest battery companies would say, 'We're going to take this and make it and give you a great deal, and you can still do your own work to improve the technology,'" or a financial backer would come and give them "a whole lot of money to start up a company."

But the Johns Hopkins scientists know it's not that easy. So every morning Poehler and Searson continue to look for the signed agreement that might bring us closer to a plastic battery reality. Despite all of the research breakthroughs, the media hype and promising meetings, it's still a dream trying to make the big leap into the commercial world. ◊

Cosmic prospector: His feet firmly planted in the desert soil, Jim Benson looks to the stars—and asteroids.

A **down-to-earth** entrepreneur with an out-of-this-world plan, **Jim Benson** hopes his company is the **first step** toward the private exploration of **space**.

Staring into Space

BY DAVID E. GRAHAM

Sipping a soft drink outside a San Diego coffee shop, Jim Benson puts a black chunk of iron on the white table in front of him. The rock is a piece of an asteroid, a talisman Benson carries as a reminder of the mineral riches that await in outer space. And this isn't an abstract interest: Benson intends his young company, Space Development Co., or SpaceDev, to be "the first publicly traded company in the business of exploring space."

If SpaceDev succeeds, Benson says, it might be quite profitable. But in his view, there's more to the venture than boosting his stockholders' profits. Indeed, he says, SpaceDev could usher in a new sector of the economy—private space ventures—that might one day have the energy and growth potential of the early software industry. SpaceDev, he believes, could hasten the economic development of the high frontier.

PHOTOGRAPHS BY CHIP SIMONS

To profitably go where only large government agencies have gone before might sound like a pipe dream, but the 53-year-old Colorado businessman is a relentless pragmatist who has a track record of success as an entrepreneur. At 50, Benson retired a millionaire after owning and operating two software companies. He sold both and set out to travel but quickly grew bored with terrestrial tourism. It was then that Benson asked himself two important questions: What do I enjoy, and what am I good at? The answers led him back to his childhood passions for science and outer space. As a youth, Benson recalls, he signed up for a science fiction book club. A benefit of enrollment was having his name placed on a list of people who wanted to go to outer space when travel became routine. He still has the enrollment card in his wallet. "Forty-two years later I'm still waiting," he says, "so maybe I can do it myself."

After consulting planetary scientists and reading up about space, Benson founded SpaceDev to aim for asteroids—little-examined and, he believes, achievable targets for exploration and eventually mining. He moved swiftly to put in place a business plan that many in the science and business community say just might work.

Teamed with researchers from the University of California (UC), Benson last September announced plans to launch bare-bones missions to rendezvous with near-Earth asteroids and inventory their mineral contents. But the craft will also have cargo space for other experiments, making it a sort of deep space truck. Planning to launch within two years, Benson wants to meet what his advisers believe is a pent-up demand in the scientific community to get experiments to space. He hopes this long-haul service will bring profits in the short term, before any mining program is up and running.

STARTING SMALL

Initial plans for Benson's Near Earth Asteroid Project, or NEAP, call for a hexagonal craft 1 meter tall and 1.8 meters across to rendezvous with one of the 450 asteroids known to pass near Earth. It will deposit an instrument to analyze the mineral content for possible future mining—perhaps of metals for construction of research facilities or power stations near the asteroid, or hydrogen and oxygen to make fuel or water. Even ordinary earth elements become exorbitantly expensive if they have to be launched from Earth, so space mining of otherwise mundane materials could be profitable—if outer-space construction were ever to become routine.

Other entrepreneurs have talked about private space missions. But most of them have foundered on the shoals of very high initial investments. The key to SpaceDev's chances of success is Benson's intention to build, launch and operate the first mission on a budget of under $50 million—less than one-tenth of what the National Aeronautics and Space Administration (NASA) frequently spent on a single craft, until recent budget cuts trimmed their sails. To achieve these economies, the NEAP craft will use what Benson proudly calls "trailing-edge technology": prefabricated solar arrays, electronics, cameras and so forth. "We're proud of the fact we're not doing anything new," Benson says. "That all increases the chances of success." And with a price list of cargo space and scientific data that totals $120 million, Benson sees the potential to turn a profit beginning with the very first mission.

Not surprisingly for such a cutting-edge venture, no contracts have yet been signed. But already, SpaceDev announced in May, seven researchers have filed notices of intent that make them eligible to apply to NASA for funding to buy a ride on the NEAP craft. For each notice that results in a NASA-approved proposal, SpaceDev would earn $10 million to $12 million in revenue.

Although skeptics might question whether a software entrepreneur has the expertise to get into space, Benson has

Destination: 1996 XB27

Measured against elaborate space ventures like Mars Pathfinder, SpaceDev's first mission plan is rather simple stuff. Over the course of eight months, a small hexagonal spacecraft will travel more than 150 million kilometers—approximately the Earth-sun distance—to reach its target. (The cube-shaped craft above is an earlier version.) The tentative destination is an asteroid named 1996 XB27; one called Nereus is a backup target.

The NEAP craft will bear three instruments: a camera for viewing and guidance, a neutron spectrometer to detect hydrogen (for potential use in the extraterrestrial manufacture of water or fuel) and a small lander. The craft will also have room for up to three additional onboard instruments or experiments, and three additional deployable canisters—those spaces are all for sale.

SpaceDev's own soda-can-sized lander will leave the mother ship and drift gently to the asteroid, carrying a proton X-ray spectrometer to analyze the asteroid's composition. In one scenario, the lander would be outfitted with a spring mechanism that would allow it to hop over the terrain and take multiple readings. SpaceDev has not settled on a launch vehicle, but a leading possibility is a Russian rocket—largely because it might be the least expensive.

managed to convince a number of people well qualified in space science. He first enlisted James Arnold, director of UC's California Space Institute. Arnold, a senior science adviser on the Apollo missions, met Benson at a conference on potential uses of the moon in December 1996. Initially skeptical, Arnold was soon impressed by Benson's knowledge, energy and business acumen. "It turned out to be a good fit," Arnold remarks, "and we have passed one milestone after another." Since the spring of 1997, a handful of scientists and students at UC San Diego have also been working to develop plans for the mission.

"If we are to get the true economic benefits of space, the private sector has to get involved... It's going to happen sooner or later."—Alan M. Ladwig, NASA

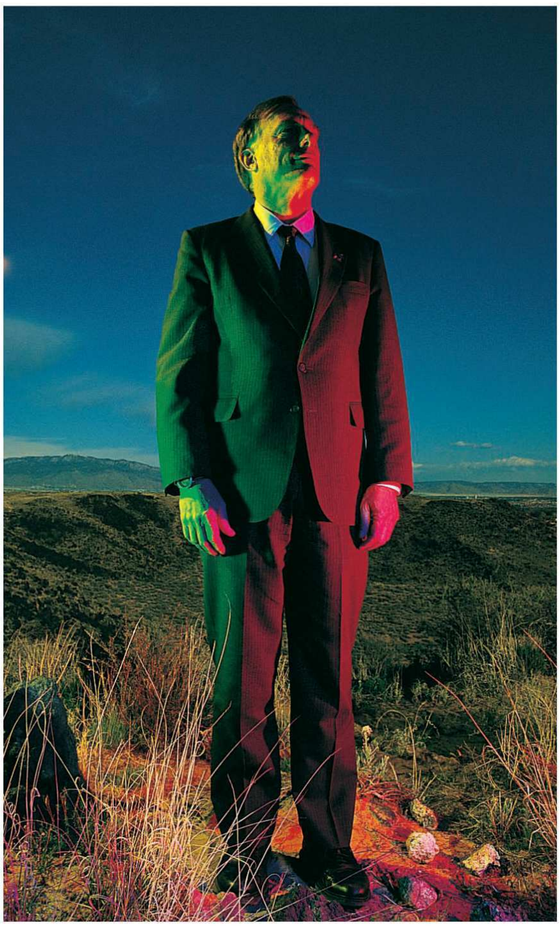
Scientific expertise, though crucial, won't be enough to get this mission off the ground; managerial know-how will also be required in spades. To fill that gap, SpaceDev acquired a small San Diego aerospace firm called Integrated Space Systems (ISS) in a stock trade this February to manage the mission development schedule and integrate the NEAP craft into a rocket. ISS's business, though modest, is already profitable. Even so, the months ahead are critical to SpaceDev's success, as it must meet deadlines for fabricating the craft and hiring a seasoned mission manager, all the while courting prospective buyers of cargo space in the vehicle.

PLAYING WITH THE BIG BOYS

In addition to shoring up his logistical base and forming alliances among researchers, Benson has already impressed another critical constituency: NASA. The agency has discussed the possibility of helping SpaceDev by allowing the company to use NASA's network of deep space tracking stations for sending and receiving radio communications with the robotic spacecraft. SpaceDev might pay for the time outright, or try to barter for it with data from radio science experiments using the craft.

"I think Jim has put together a very credible approach to what would be the first private exploratory mission," says Carl Pilcher, a NASA assistant associate administrator for space science. "If he can pull it off, it will be an interesting precedent for a new way to acquire scientific data." Pilcher praised the abilities of the scientists involved and their plan, saying he believes they "are capable of delivering on what they promise."

Benson believes that if he can get one craft into space, other opportunities will follow. Perhaps SpaceDev would help NASA in its plan to explore Mars by providing some services faster and at a lower cost than NASA can, he says. Possibilities include ferrying a communications relay satellite into orbit around the planet, or depositing equipment on Mars that would mix hydrogen and oxygen to produce fuel. NASA's Pilcher says the agency would listen to arguments for such deeper private participation.



ANY TAKERS?

NASA's associate administrator for policy and plans, Alan M. Ladwig, shares Benson's belief that the time is right for private ventures into space. "If we are to get the true economic benefits of space, the private sector has to get involved, so we encourage that," Ladwig says. "It's going to happen sooner or later." But Ladwig cautions that SpaceDev will have to find markets beyond NASA.

Finding a suitable market has been a challenge for Benson's competitors in the business of launching private space missions. Michael Simon, the president of San Diego-based International Space Enterprises, has firsthand experience with the problem. Simon wanted to launch payloads to the moon on Russian rockets. But finding it expensive and having few takers, his company is now designing hybrid-power road vehicles. Though Simon praises Benson for shrewd organization and for keeping startup costs low, he adds that "for Benson it comes down to the same question that haunts all of us in the industry: 'Is there a market?' And if there is, yes, he can pull it off."

For his part, Benson remains a believer. A veteran of the computer revolution, he believes the private space economy—using the energy of the private sector and building on the contributions of the government agencies that pioneered the field—might develop rapidly and surprise people, as the computer industry did two decades ago. In this scenario, he believes, SpaceDev could be midwife to a broader human presence in space, an era in which people not only explore but also build, work and perhaps even live beyond the confines of Earth.

Benson wears a wrist-watch that is already counting down the seconds until SpaceDev's first liftoff, tentatively scheduled for October 3, 2000. "This could be a wake-up call," he says, "that the time has come to commercialize space." ◊

The hard part is not predicting technology—it's predicting how people will use it, says Robert W. Lucky, telecommunications wizard of Bellcore

A Lucky Hit

Q & A

The world was simpler back when young electrical engineer Bob Lucky started work at Bell Labs. Telephones were sturdy black appliances with dials. Fibers were something clothes were made of, and webs were for spiders and duck's feet. Computers were huge, expensive and scarce.

Fast-forward to 1998, and Lucky still exudes awe at all that has come to pass in the intervening years. But his awe is not that of the ingenuous outsider, since Lucky had no small hand in this rapid progress. He is credited with inventing the adaptive equalizer—a technique for correcting distortion in telephone signals that is still used in virtually all high-speed data transmission. He literally wrote the book on data communications, writing a text that was for years the bible of the industry. But outside the community of communications engineers, Lucky is best known as a sharp and witty commentator on the ways technology infiltrates our lives. He radiates enthusiasm for technologies that he likes (such as e-mail) and disdain for those he doesn't (such as voice mail).

Since leaving Bell Labs in 1992, Lucky has been corporate vice president for applied research at Bell Communications Research, or Bellcore. As the research arm of the telephone companies, Bellcore is on the front lines of the telecommunications revolution. Lucky spoke with *Technology Review* senior editor Herb Brody in his office in Red Bank, N.J.

TR: What do you think makes an organization innovative, and how has that changed over the time you've been involved with R&D?

LUCKY: Innovation is a difficult thing. I have lost some of my faith through the years in all of the systems that we know about. I worked a long time at the old Bell Labs, where you'd hire the best people, you'd give them money and let them do their thing. We sponsored a lot of intellectual quests that way. There used to be a plaque over the entrance to the Murray Hill Lab of Bell Labs with a quote from Alexander Graham Bell. It said something like: leave the path and dive into the woods, and you'll be surprised at what you find. The idea was to go out there and explore, and to build the best telephone network there is. We had no conception of making money. It was almost a religious thing. There was an honest

PHOTOGRAPHS BY KEVIN KNIGHT

respect for science and technology and the days would go by with arguments over scientific points. It was the way life should be.

TR: Of course, this system produced some dead ends as well as some fabulous technology.
LUCKY: It certainly did. With R&D decoupled from the market, a lot of ideas fell on barren earth and never grew up. And ideas by themselves are pretty worthless—somebody's got to take them and make it happen. Over the years, I have gained a lot more respect for the people who turn ideas into realities. Now we're in a world where ideas are judged only by market utility. And in the market world, you don't allow people to wander in the woods. I regret this, but I can't afford to have people who are just crashing around looking at crazy things. Even though, historically, these are the kinds of people who make the biggest breakthroughs.

TR: What's an example of the old system of innovation going astray?
LUCKY: Picturephone is a classic case. It was decided that this was the way that communication would go. The funds were immediately made available—armies of scientists and engineers were mobilized, the technology breakthroughs were scheduled and made. The service was offered. Then nobody wanted the thing. But that was OK according to our mindset at the time. If picturephone was what was right, we could do it, because we had total control over it.

TR: Conventional wisdom these days is that the market has to play a much stronger role in driving technology and in setting research directions—that this is how to make innovation productive.
LUCKY: That is the theory, and it's generally true that the market stimulates innovation. It's hard to know where the truth lies because we're not running a controlled experiment. But I do worry that the pure market focus will lead us to ignore some research of great value. I also think that in places like Silicon Valley, the pressures to make money have become too strong.

TR: Isn't that what business is about?
LUCKY: Primarily, but not entirely. A lot of the innovators that I've known have been driven by the desire to produce something that helped people in their lives or work. Financial reward was important to them, but not their overwhelmingly dominant incentive. Now I get a sense that the whole object is to start a company and take it public and make a lot of money. This really discourages me.

TR: In telecommunications, the field you know best, is industry dropping the ball anywhere?
LUCKY: One of the things that everybody wants is broadband access to the home. And if you were running the world, you'd say, hey, let's just put fiber out there in the homes, we'll have all the bandwidth we want. But that's not happening because of the risk of stranded investment. You dig up the streets, you put the fiber in and a guy comes along with a wireless solution and you've dug up the streets, the money is gone. The risk of investment here stops this from happening. So there's a case of the market prohibiting a development that everybody agrees is needed. Also, I'm bothered that senior management is still essentially clueless about the Internet. According to a recent poll, more than 60 percent of executives think the Internet is owned by a corporation; 23 percent think it's part of Microsoft. The good news is that 98 percent of sixth-graders polled knew that nobody owns the Net.

The Net from Nowhere

TR: For most people, the Internet arrived on the scene a few years ago with little advance warning. What does this tell us about the emergence of world-changing technologies?
LUCKY: The Web is an astounding example of lack of foresight. Nobody foresaw this—in industry, or anywhere else. In retrospect, the Web is the most obvious thing you ever heard of, and it is such a world-class idea.

TR: But the telecommunications industry was looking the other way, basically.
LUCKY: Yes, the phone companies were fixated on centralized systems. We had a number of home information system trials, with video-on-demand as the main attraction. Nobody thought, hey, why don't we just create an infrastructure and let the *users* supply the informational content—which of course is what has happened. Industry really didn't have a lot to do with it. Also, one big reason the Web took off the way it did was that Mosaic—the first graphical Web browser—was developed at the University of Illinois and was made available for free. This turned out to be key, because nobody is going to *buy* browser software when there's nothing to browse. That set a model that Netscape and then Microsoft got locked into, where browsers were free and users generated information. I suppose you could have made picturephone ubiquitous too, if you mailed a free one to everybody overnight. But what business would ever come up with a model that revolved around giving away your product?

TR: This kind of thing reinforces how difficult technology forecasting is.
LUCKY: Yes, and I have stopped consciously trying to predict the future. I'm out of that game. I'm a member of an industry that has been driven by several compelling visions over the last decades. One was picturephone. Another was home information services—mainly video-on-demand. Finally, there is ISDN [integrated services data network]. These are visions that mesmerized the telecommunications and computer industries, and they ended up being just plain wrong. The hardest part is not so much predicting what technologies will come about but in foreseeing how people will use them. That's where we have been wrong all the time.

TR: A lot of industry pundits still can't resist crystal ball gazing, though.
LUCKY: I know. I was at a meeting a few years ago at Microsoft where Bill Gates gave us his vision of the way things were going. I wrote it all down. I think it has all turned out to be wrong. My old boss, George Heilmeier, tells about being in a bookstore last year and seeing this giant stack of Gates' book—*The Road Ahead*—by the checkout counter. On each book was a sticker saying that it was "recently updated to include the Internet." I mean, if you can't see the Web coming, what good are you?

TR: Kind of makes you wonder what else is going to blindside us.
LUCKY: Yes. But you know, there hasn't been anything else of that magnitude for a while. Maybe the Web is it for a while. Maybe it's like that punctuated equilibrium theory of evolution, where you have long periods of stability interspersed with occa-

sional epochs of intense changes. Maybe we're in an equilibrium state, and nobody has a vision beyond the Web right now. Maybe the Web will turn into a broadcast medium and take over from radio and television—who knows? I don't, and I don't believe anybody who says they do.

Technological Ambivalence

TR: Do you agree with many pundits that the next computer revolution will come from speech-recognition technology?

LUCKY: That's a vision that people have had for a long time. But we're not even close to having a Hal-like machine that can converse with us intelligently. And frankly, I'm not even sure I want to talk to my computer. This might be another example of an equilibrium state; maybe the mouse-icons-windows interface is going to be around for a very long time. Nothing better has come along.

TR: Another proposal to broaden computer use is to market inexpensive "network computers" that derive their power from the Net.

LUCKY: I think this is a dumb idea. When I give talks, I often ask the audience, how many of you would like one of these? Nobody raises their hand. It's basically a control issue. Corporate CIOs would like to control the information infrastructure.

TR: Do you have any regrets about where technology has brought us?

LUCKY: Well, we benefit from the connectedness of the Web and e-mail and pagers and cell phones and everything. But I resent that these information tentacles are reaching out for you all the time, sucking you in and pulling you down. I find this a bigger and bigger personal burden. I just can't seem to have it both ways. I thought early in my career that the goal of telephony was to have the Dick Tracy wristwatch phone—until the day I realized that when I have one, the world can call me at any time. I don't want that—the world's a big place.

Network computers? "A dumb idea," says Lucky. He often asks his audiences who would like to own one. The result: "Nobody raises their hand."

TR: Is this part of the fashionable griping about "information overload?"

LUCKY: It's not quite that simple. With e-mail, for instance, it's annoying to have to deal with too many messages—100, say, is too many. But if there are too few, then the world has forgotten about you, and that's scary. If I come in in the morning and there are only 10 e-mails, I get really nervous. The ideal number is somewhere in between—probably around 25.

TR: A similar tradeoff applies when you're doing searches on the Web, doesn't it?

LUCKY: Yes—I either get 10,000 hits or zero, and I never seem to find what I'm looking for. One expert told me that the search engine wasn't failing—I was just incompetent. I didn't know how to craft my queries. She may be right, but I said, look, that's your problem. You're giving me this complex query language stuff and expecting me to be able to master it. You're just not meeting the market demand for a really easy, powerful search tool. And this is important—search engines are the key to the universe right now.

TR: Do you look at the Web as a giant library?

LUCKY: I think it can be a lot better than that. It's really a library filled with *people*. If you tap into the wisdom of the people in the library, together with the books, then that's what will make a real difference. Often in life when you want to find out something, you ask friends and you ask experts in that field, and they point you to stuff that they think is good. But the search engines on the Net are sort of disembodied right now—they have none of that wisdom in them about what might be really good out there.

TR: What do you fear is being lost in the digital age?

LUCKY: We're not producing artifacts of our work in progress anymore. Go to the British Museum and look at their manuscript section. They have handwritten things from Mozart and Shakespeare. When you see the Bach manuscripts and you see that he scratched out that note and changed it to the one that you now know—that's awesome. And when you write on a computer, that kind of document doesn't exist.

TR: How is the world different than you imagined it would be when you were young?

LUCKY: When I got out of school, I somehow pictured a static world. Now, I have this concept that it's all shifting sands under our feet. Everything's changing all the time. Complexity is accumulating all around us. In the old days, the Bell System had monopoly control of the phone network. That was one extreme. Now, things have swung way the other way, and nobody has any control anymore of what's going to happen. We're just being tossed in this angry sea. On the other hand, developments like the Internet are fantastic. I'm just so happy that my career has spanned this development, so that I can see what the telephone was really meant to do. ◊

VIEWPOINT | *By John Maeda*

The South Face of the Mountain

In Japan, a *miyadaiku* (a carpenter trained in the ancient art of Japanese temple carpentry) attains special status from the Emperor if the temple he builds stands for more than a thousand years. "Such temples," said one of the last *miyadaiku,* the late Tsunekazu Nishioka, "stand not because of the magnificence of their design, but because the *miyadaiku* goes to the mountain, and selects trees from the south face of the mountain to be used for the south face of the temple, trees from the west face of the mountain for the west face of the temple, and so on for the other two sides." Because the building materials are carefully selected in order to respect the laws of nature, the temple can coexist in harmony with nature. Both the extrinsic and intrinsic qualities of the temple radiate its overall strength and beauty.

Whether we accept the specifics of the *miyadaiku*'s explanation or not, the metaphor of harmony between the materials and the work of art is a powerful one. Indeed, although this story might seem quaint and old-fashioned, we can use it to explain the situation in the most high-tech of contemporary fields: computer art.

With a very few exceptions, all of today's computer art represents a collaboration between an artist and an engineer. The artist has the conception, but it is the engineer who understands the materials—the hardware and software—needed to realize this conception. This is very far from the harmony envisioned by the *miyadaiku* between conception and realization, materials and design. In fact, in today's computer art, the artist assumes the role of the creative genius while the engineer settles for the subordinate role of manual laborer. Although such collaborations can produce respectable artwork, they rarely lead to works of real power and inspiration. What is more, the situation is getting worse because relentless progress in information technology has widened the gap between artist and engineer: The artist has little understanding of the computer as a medium, and the engineer (who has no artistic training) is not allowed to unlock his creative potential in using the medium he has mastered.

How can we heal this split and unleash the deep creative power that is inherent in the new medium? I think the answer lies in re-engineering our teaching so that the same person can be a fully formed computer artist—both conceptualizer and engineer in one person. Not that I think this will be an easy process. Actually, today it is still a very difficult process, and one that can only be accomplished after significant trial and error, as my own career demonstrates.

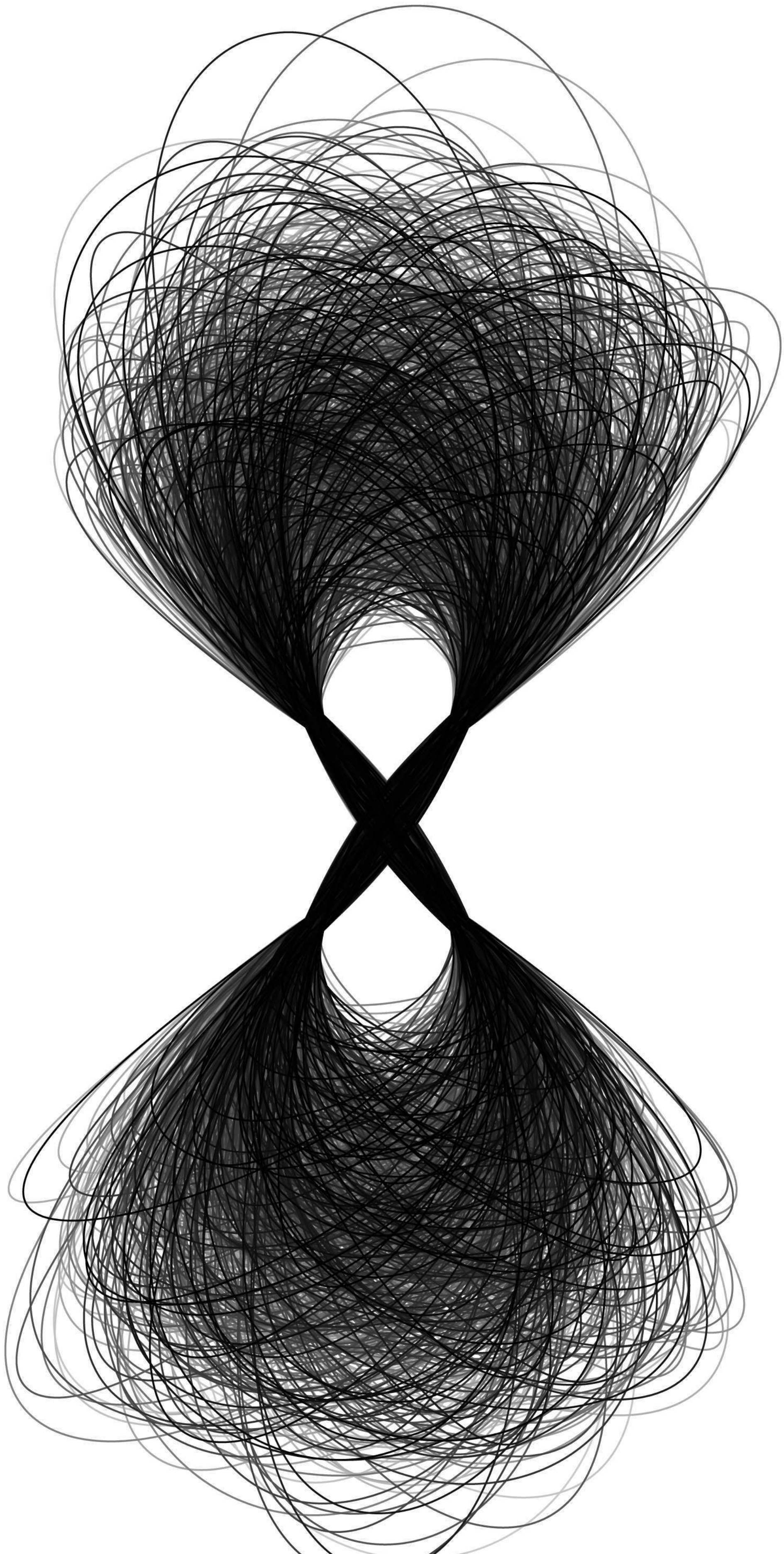
Being proficient at both art and mathematics, I found it difficult to choose a major when I arrived as an undergraduate at MIT in 1984. However, as the dutiful son of a practical-minded father, who told me I would never make a living drawing "pretty pictures," I naturally chose the very practical and employable discipline of electrical engineering and computer science. I continued to pursue design as a hobby, and I would often venture into the various technology/art venues on campus seeking an undergraduate research fellowship that would combine my interests. However, the majority offered not an opportunity to achieve mastery in the arts, but instead a chance to fill the need of many artists for fluent technologists who would help develop incremental improvements in their efforts. My true salvation was the Rotch Library on campus, which houses a rich

My father startled me by declaring that I was now a man and free to pursue my own interests. I immediately left for Japan to study graphic arts in the traditional manner.

collection of examples of graphic arts, where I could delve into generations of "real" artists and see a depth to their craft that I could not find on campus.

I persevered in my "practical" study of engineering until I had earned my master's degree. At that point, my father startled me by declaring that I was now a man and was free to pursue my own interests. Liberated by his permission, I immediately left for Japan to study graphic arts in the traditional way.

In 1990 I entered the Institute of Art and Design at Tsukuba University. Tsukuba was a Bauhaus-influenced arts and design school with very few computers (there was only one Macintosh on hand), and I was suddenly free from the daily e-mail grind. The absence of high technology was very calming, as was the traditional atmosphere. I experienced a sense of gratitude for being able to think with my hands in harmony with my mind. I had been taught to honor tradition from an early age, and so the didactic ways of art school suited me very well; I was pleased to steep myself in the graphic traditions of the Japanese masters in such arts as typography, fine printing and sculpture.



AROUND THE TIME I WAS COMPLETING MY STUDIES at Tsukuba, however, I got a surprise not unlike the one I had received from my father on getting my master's degree. My very traditional-minded instructor in typography, Professor Kiyoshi Nishikawa, pulled me aside and advised me to stop studying the classics. "Do something young," he said. "The classics will never change; they will be there to honor when you are old." The time to make a significant contribution to the design of our times is now, he told me.

Liberated again, I returned to the computer, and, after the traditional discipline I had experienced for four years at Tsukuba, I was amazed by the feats I was capable of. I could make lines that move, change color and stretch in all directions; I could make a million lines, duplicate them twicefold and delete all of them in a single command stroke. When I was at MIT, this was all a very natural thing to do at the computer; however, having been away from computers in a very different environment, I had become so accustomed to a rule and pen that I was bewildered by the possibilities posed by the computer. I had a new sense of respect for the potential of the medium and set out to explore the expressive gamut, creating a series of images for my first exhibition "Design Machines" *(page 77)*. The images exercised the computer's ability to create complex imagery.

In the development of my key image, I was interested in enscribing an image of "infinity" as a series of loops that never terminate, and created a self-terminating shape of linked splines. Reviewing my work, Dr. Edward David (former science advisor to President Richard Nixon and a person with close ties to MIT) referred me to work created in a similar spirit during the 1960s at Bell Laboratories, the birthplace of computer art. I discovered that many of my techniques, such as making pictures out of small pictures, endless textures of lines and noise-based images, had already been used by the pioneers at Bell Labs.

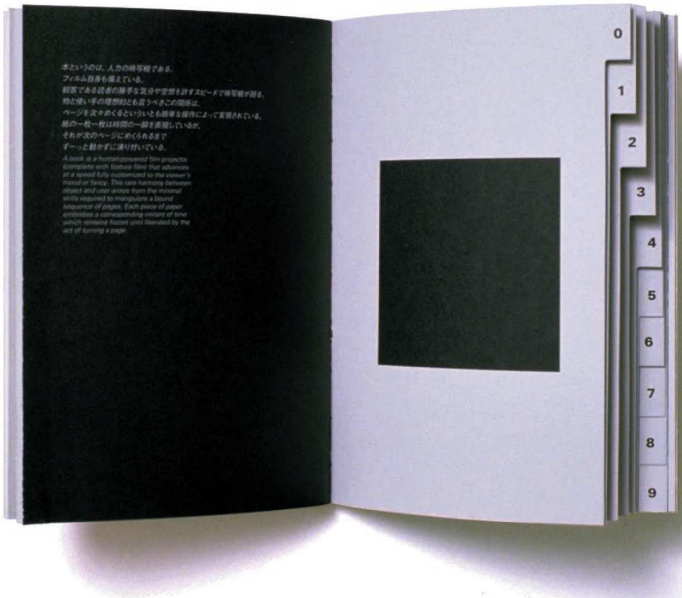
At first I was discouraged and considered early retirement from the field, returning to studying the classics. However, after many hours of staring at work by my predecessors, I realized that although the concepts employed were similar in spirit, there was considerable room for improvement. It was as if a visual sleight of hand had been performed, but the trick had not been perfected. The computer had simply been used as a substitute for paint brush and paper, rather than being explored as a medium in its own right. As a result, there had been no opportunity for technologists to develop into true digital artists. With this conclusion, I set out to develop myself as a true artist-engineer, with the computer as my medium. And I also have dedicated myself to nurturing a generation of people with this same potential as both engineers and artists.

In my own creative work, I pursue this art form both in print and in the digital displays on the computer screen. In print, I search for the simplest means for realizing visual complexities that carry an orderly theme; in digital, I spin complex weaves of temporal graphics that appear simple because all of the details have been hidden along the axis of time. Five years ago, I began to create a mixture of print/digital work that emerged as a popular series called "Reactive Books." In this endeavor, I focused on developing not just "interactive" media, but "reactive" media, where the interaction hits at a more sensorial level *(opposite page)*.

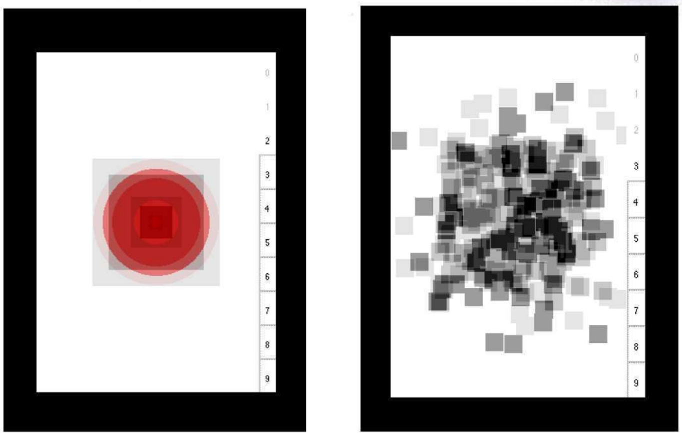
When I showed this work to the late designer Paul Rand (a master best known for designing the IBM logo), his wise response was: "This is all quite beautiful work...but how are you ever going to make any money doing this?" I found this odd coming from a designer. In fact, I felt I was back to square one—my father's earliest advice. But Rand wasn't referring to an artistic career in general but specifically to the fact that there was no market for the kind of work I was doing. Nobody was about to buy a floppy or CD-ROM to look at one of my dynamic pieces because it was simply too inconvenient and expensive. The answer to this dilemma came with the birth of the World Wide Web and the emergence of the JAVA programming language. With those two developments, possessing a mixture of graphics and computational skills began to achieve commercial relevance. One client stepped forward before all others, an art director at Shiseido Cosmetics, Michio Iwaki. In the 1960s, Mr. Iwaki had experimented with computer art while he was in design school, but his fellow students made fun of him for "not being able to use a regular pen." He gave up mixing design and computation, but swore to support the effort one day. Still images from my series of JAVA calendars for Shiseido is shown in *(page 80)*.

This developing combination of graphic arts and engineering skills, along with my gratitude to teachers at MIT, brought me back to Cambridge two years ago to help instill these principles in a generation of young digital artists. I had been recruited to resurrect the Media Lab's waning presence in computationally motivated graphic design, which only several years before achieved international recognition for ideas and practices initiated over decades at the lab's Visible Language Workshop (VLW) by the late Professor Muriel Cooper. Today at the Media Lab, my research group is called the "Aesthetics and Computation Group," and we are devoted to combining analytic and expressive skills in singular expressions of will and technology.

"Do something young!" my teacher said. "The classics will never change; they will be there to honor when you are old." The time to make a contribution is now, he said.



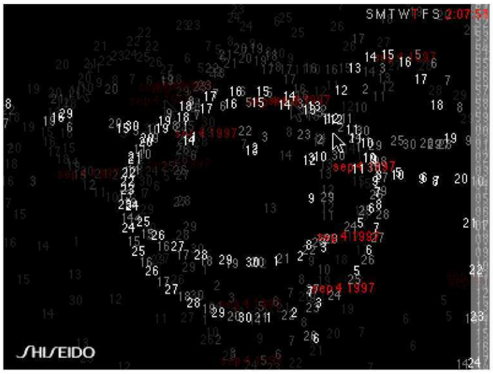
"The Reactive Square" was a reactive book—published as both a floppy disk and as a more conventional-looking book. Its theme: a simple black square as a starting point for design.

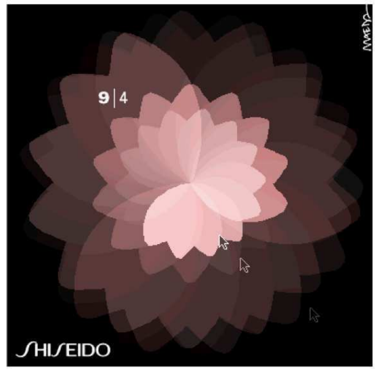


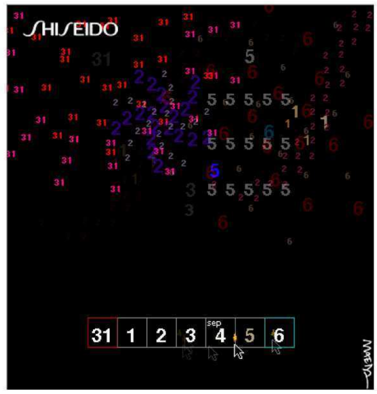
"12 o'clocks," a reactive book whose pages were created by the same software that runs the clocks contained in the floppy disk.

"Flying Letters," a reactive book that unfolds like an accordion, was the last reactive book to include a floppy disk. Its subject is typographic design.

Still images from a series of calendars done by Maeda for Shiseido, the Japanese cosmetics firm. The calendars were written in the JAVA programming language for the World Wide Web.







I very much enjoy what I am doing with my group of young artist-engineers. But I believe that these same principles must be applied much more widely, throughout MIT and indeed throughout our university system in general. At least at MIT, there has been for many years an awareness of the need for combining the humanities and sciences at the curriculum level. Despite the best of intentions, however, the model of training is this area remains some form of the humanities wrapped around technology, or vice-versa. But we must go far beyond this initial model. It is not enough for us simply to produce a technologist who is aware of the cultural context of technology or a humanities major who can talk fluently about technology. No. What is needed is a true melding of the artistic sensibility with that of the engineer in a single person.

Although this task will not be easy, I have an idea of how it could be done. What is needed is an initiative at MIT—and at other universities—that combines the skills imparted in basic engineering courses with those found in humanities classes. For example, here at MIT one of the largest undergraduate courses is the introduction to computer programming (known as 6.001, because it is the first step in "Course VI," which is the electrical engineering and computer science major). The spirit of 6.001 needs to be combined with some of the basic humanities courses, such as art history or beginning photography. In this context, the prejudices of both sides—engineering and humanities—could be relaxed, and students would be able to begin to combine the core principles of both disciplines. This may seem like an abstract, even quixotic idea, but at the Media Laboratory, I have begun to teach courses in this manner—and it works. In these courses, gifted young engineers and scientists are beginning to stir their creative talents as the designers and artists of the next century. But we will see this next generation of art and artists only by gaining a deeper understanding of, and appreciation for, the medium of computing as a means of serving human expression. ◊

We need a true melding of the sensibility of the artist with that of the engineer—it is not enough to train humanists with a little engineering familiarity—or vice versa.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Blue-Collar Cell Therapy

AMONG HIGH-CONCEPT FORMS OF MEDICINE, FEW approaches have as much intuitive appeal as cellular therapy. The idea is disarmingly simple—remove homegrown cells from the patient's body, grow them to vast numbers in the lab and then give them back as medicine. It has already been attempted in a few instances against cancer. Remember the TIL cell—"tumor infiltrating lymphocytes"—craze of the 1980s?

But perhaps the most interesting cellular therapy to date, and the only one to receive the blessings of the Food and Drug Administration as a bona fide biologic intervention, involves not one of the body's vaunted cellular paladins, such as lymphocytes or neurons, but rather a blue-collar cell known as the chondrocyte. These cells provide the cushion known as cartilage between joints, and for the past three years, orthopedic surgeons in this country and Europe have been using them to rebuild knee joints denuded of cartilage by acute or repetitive trauma.

Using the body's own cells as medicine is a concept with huge potential. A new method for replacing knee cartilage is the first to put the idea to commercial test.

Like many new technologies, this one had a fitful and peripatetic evolution. The initial idea was explored in the early 1980s by a group of surgeons at the Hospital for Joint Disease in New York, including Mark Pitman and a visiting surgical colleague, Lars Peterson. They reported preliminary results in 1984 of cartilage implants in rabbits.

Peterson returned to the University of Goteborg in his native Sweden, where he hooked up—at the suggestion of a tennis partner—with Anders Lindahl, an expert in cell culture. The team ultimately developed a method for culturing cartilage cells and implanting them in humans and received approval to perform the first human implant in 1987, using a technique that is now being taught to more than 2,000 orthopedic surgeons in this country. (The Cambridge, Mass.-based Genzyme Corp. became involved in 1995 when it acquired another company, BioSurface Technology, which was also working on the technology.) The Food and Drug Administration approved the treatment method in August 1997.

At the present time, regulatory approval is limited to procedures that treat the part of the femur (the long bone of the thigh) that meets the knee. When the knee joint is damaged, either in an acute injury such as a skiing accident or by more gradual wear and tear, the cartilage lining the thigh bone where it joins the knee often becomes damaged. This tissue rarely regenerates, and the erosion announces itself with locking, catching, swelling and pain.

According to the procedure developed by Peterson, surgeons harvest a tiny snippet of healthy cartilage arthroscopically. This biopsy sample—about the size of a thumbnail clipping, according to Ross Tubo of Genzyme Tissue Repair, a subsidiary of Genzyme—is then sent to a cell culture laboratory. This bit of tissue, a mere 100 to 200 milligrams, is roughly 99 percent cartilage and 1 percent chondrocytes, the cells that actually make cartilage. So the sample must be digested to separate the cells from the matrix before the cells can be cultured.

After some three or four weeks, there are enough cells for an implant—roughly 30 million cells per milliliter of fluid. They are sent back in vials to the orthopedic surgeon, who performs traditional methods of knee surgery to insert the cells (researchers are also working on ways to deliver the cells by arthroscope).

Genzyme Tissue Repair began to market the cell-culturing service, which they call Carticel, in 1995. Since that time, more than 1,000 patients have been treated with a joint-restoring medicine that in a sense is of their own making. The procedure is not cheap: Genzyme estimates that the average cost is about $26,000. But the company has mounted a vigorous effort to get insurance companies and health maintenance organizations to reimburse the operation.

Sometimes the transplanted cells work too well. The most frequent side effect appears to be what is known as tissue hypertrophy—an excessive growth of cartilage. In one follow-up study, 43 percent of the patients had some degree of excess tissue growth in the implanted joint. On the other hand, early data suggest that the technique is in many cases quite successful for the optimal patient population—those between 15 and 50 years of age.

And the treatment appears to be durable. In a recent presentation to the American Academy of Orthopedic Surgeons, Lars Peterson reported that in a group of 38 patients who received a cartilage-cell transplant more than five years ago, 31 patients were judged to have had a good-to-excellent result two years after the procedure, and of those, 30 continued to show good-to-excellent results five years after.

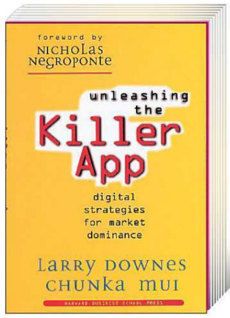
Peterson has already applied the basic technique to patients with ankle and shoulder injuries in Sweden, and perhaps it's only a matter of time before the phrase "autologous cultured chondrocytes" will trip mellifluously off the tongue of ESPN anchormen as they describe the cellular rescue of one more superstar fetlock. "I don't know of any professional athlete that has used the procedure," says Tubo, "but it certainly would be applicable to a career-threatening injury where you have a pothole in the middle of your cartilage." ◊

PAGES *The best new books on innovation*

REVIEWS BY WADE ROUSH

Zen of the Net: Devour Yourself

Established businesses have always had to worry about the power of technological change to generate fresh competition. But the question managers will have to ask themselves if they want to survive the current explosion in digital commerce is more gut-wrenching than ever before, warn technology consultants Larry Downes and Chunka Mui. What if a company suddenly appeared that could offer the same products or services as yours, at lower prices, in a way that's more convenient for customers—and at far less cost to itself? In other words, what if the new "killer app" came along and you were the prey?



UNLEASHING THE KILLER APP: Digital Strategies for Market Dominance
by Larry Downes and Chunka Mui
Harvard Business School Press
243 pp. $24.95

That's the power the Internet and related technologies are giving to new businesses, Downes and Mui assert. As one example they cite Barnes & Noble bookstores, which have classically profited by providing a vast selection and volume discounts. This service requires that acres of books be stocked at each store. But a Web-based bookseller such as Amazon.com, because it deals in "bits" rather than "atoms," can offer an even greater selection without having to build a single store or stock a single book. The Web, in this sense, is one vast killer app that threatens to do away with traditional retailing.

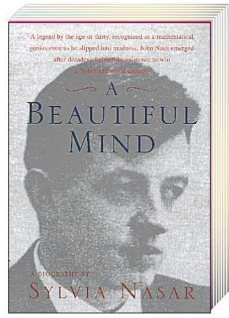
Hence one of the dozen provocatively counterintuitive principles of digital strategy that Downes and Mui offer to managers: Treat your perceived current assets as liabilities. "It's important to shift your investment to bits, because those new competitors that have *none* of your fixed assets—no real estate, no manufacturing equipment, no distribution network—will suddenly look competitive in the new business environment," they write.

Shifting to bits and inventing your own killer apps—in essence, devouring your own business model before you get devoured—won't be easy, and at many points Downes and Mui imply that if you haven't yet started, it may be too late. But the doomsaying, in the end, gives way to the radical yet well-reasoned counsel that makes the book truly eye-opening.

Score One for Hope

Raw genius is often required to intuit the hidden connections between an established mathematical truth and an unsuspected result, and arrogant self-confidence to undertake the formal proof. But the disturbing implication of *A Beautiful Mind*, a masterful biography of the Nobel Prize-winning mathematician John Nash, is that these same qualities may leave their holders unusually prone to mental illness—especially the mysterious disorder known as paranoid schizophrenia. Unchecked insight detects hidden connections everywhere, Nash's case suggests, and unchecked egotism spawns grandiose delusions.

Nash was a mathematical prodigy who earned his Ph.D. from Princeton in 1950, at the age of 21. His thesis on game theory transformed the field from an academic curiosity into one of the foundations of modern economics, sociobiology and business strategy. He proved that not only for noncooperative zero-sum games, where players' interests always conflict, but also for the far more common class of cooperative, non-zero-sum games, where players have both common and conflicting interests, it is always possible to predict each player's most rational strategy.



A BEAUTIFUL MIND
by Sylvia Nasar
Simon & Schuster 464 pp. $24.50

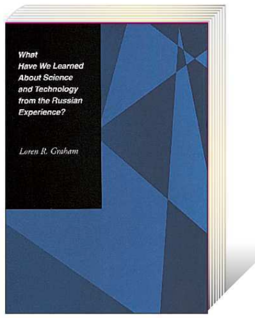
By the time Nash was 31, his ingenuity and persistence in the face of daunting problems, as well as his air of superiority and his frequently adolescent behavior, had already made him a legend in the mathematical community. But that was when Nash lost his own grip on rationality. According to this vivid, unsparing account by Sylvia Nasar, an economics correspondent for *The New York Times*, Nash ceased doing mathematics and fixated on the idea that he should form a world government. He delved deeply into numerology, finding messages meant for him in other people's names and in newspaper articles, and turned against his wife and family. "Where once he had ordered his thoughts and modulated them," Nasar writes, "he was now subject to their peremptory and insistent commands"—a good pocket definition of schizophrenia.

Nash's sudden descent—and the three decades he subsequently spent as a patient in mental hospitals, a world traveler on a bizarre quest for political asylum and a wraith haunting the halls of Princeton—both horrified and fascinated his colleagues. "All you have is your brain," one former Princeton economics professor told Nasar. "The idea that anything could go wrong with it...[is] threatening for everybody, of course, but for academics that's all of it."

Yet Nasar doesn't let the lurid spectacle of Nash's mental disintegration eclipse the larger themes in his life that may have prepared the way for his illness: loneliness and fear of intimacy, disdain for social and scholarly conventions, propensity to live in a world inside his own head, repressed homosexuality. And she doesn't neglect the story's remarkable dénouement: Nash's gradual recovery from schizophrenia in the 1980s, and his selection, along with two other pioneers in game theory, as a winner of the 1994 Nobel Prize in economics. This happy conclusion to Nash's wasted years, so different from the endings of other troubled geniuses such as British mathematician Alan Turing, scores one for hope over despair, and elevates Nasar's well-told story to the level of high drama.

Peering in at Soviet Science

MIT PROFESSOR LOREN Graham, the United States' foremost historian of Russian and Soviet science, doesn't publish fat tomes every decade or so as many of his peers do; he writes topical, digestible books that invite his audiences along on his scholarly travels. His last short book, The Ghost of the Executed Engineer, came out in 1993 and told the appalling story of Petr Pal'chinskii, a Russian engineer repressed and ultimately executed for his humanitarian scruples. Graham's latest book is broader in scope but still manages to weigh in at less than 200 pages. To use his own phrase, it is another "small book about big questions."



WHAT HAVE WE LEARNED ABOUT SCIENCE AND TECHNOLOGY FROM THE RUSSIAN EXPERIENCE?
by Loren Graham
Stanford University Press 177 pp. $39.50 cloth, $14.95 paperback

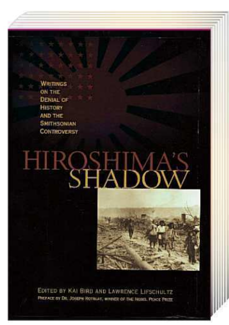
The first question Graham takes up is fascinating, but it may be "big" only to those familiar with the ongoing debate in academe over the epistemological nature of science. Does it refer to an objective reality, or is it a social construction, inextricable in style and content from the culture and the times that produce it? Graham, an exceptionally clear-headed thinker in a field rife with sophistry, uses the Soviet example to show that it is both. Lysenkoism, a disastrous agricultural policy built on the Lamarckian idea that acquired characteristics can be inherited, enjoyed a 30-year reign in the Soviet Union because it accorded so well with Marxist principles, Graham explains. But facts, not philosophy, proved Lysenkoism's undoing in the 1960s, as Western farmers outperformed their Soviet counterparts and Western biologists gathered irrefutable evidence on the existence and nature of genes.

Graham addresses several other, more pressing questions equally astutely. Are science and technology Westernizing influences? How willing are scientists to reform their own institutions? Who should control technology? And which is more important for science's survival: political freedom or financial support? To this last question, Graham has a disturbing answer. "The Soviet Union politically repressed science atrociously while simultaneously supporting it financially more fulsomely, relative to its resources, than any other country in history," he writes. Sometimes, the investment paid off in the form of successes such as Sputnik. "The sobering conclusion that we must draw, in terms of scientific results, is that the support counted for more than the repression."

Graham's premise throughout is that science and technology are transnational pursuits, and that if we hope to distinguish their essence from their variations, we had better ask how they performed so well in the Soviet Union, under social conditions so strikingly different from those in the West. "If we answer this question, we shall learn as much about ourselves as we shall about the Soviet Union," he writes. And that would be no small achievement.

The Long Shadow of the Bomb

THE SECOND WORLD WAR WAS THE Good War from the Allied perspective, but no nation escaped the vicious conflict with its standards of moral conduct unaltered. The biggest change was probably the breakdown of the prewar consensus that cities and civilians are not legitimate military targets. Germany's destruction of Rotterdam and Japan's violation of Nanking were repaid by the Allied firebombings of Hamburg, Dresden and Tokyo. And after these eradications, it must have seemed a small step to President Harry Truman and his advisers to use atomic firestarters over Hiroshima and Nagasaki, killing some 200,000 Japanese civilians.



HIROSHIMA'S SHADOW
Edited by Kai Bird and Lawrence Lifschultz
The Pamphleteer's Press 584 pp. $39.95

Many contemporary critics, however, blanched at the new level of horror the atomic bombs visited on noncombatants, including *Time* magazine founder Henry Luce, the Federal Council of Churches, Albert Einstein—even Dwight D. Eisenhower. Why, then, did the draft script for the 1995 *Enola Gay* exhibit at the Smithsonian Institution's National Air and Space Museum, which presented the full historical debate over Truman's decision, provoke a firestorm of indignation hot enough to cause the original exhibit's cancellation?

Hiroshima's Shadow offers a wealth of explanations and rejoinders for what its editors call this "denial of history." The exhibit's foremost fault may have been foolish timing. Veterans and other Americans celebrating the 50th anniversary of V-J Day were in no mood to dissect the moral and political complexities of the war's endgame. But more to the point, much of the public apparently remains satisfied with Truman's postwar justification that using the bombs was the only alternative to expending the lives of up to 1 million American soldiers in the planned invasion of the Japanese home islands.

In more than 60 archival documents and new essays by prominent historians such as Gar Alperovitz, Barton Bernstein and John Dower, the book lays this notion securely to rest. Military and political leaders knew in the summer of 1945 that Japan was on the brink of surrender, and that the invasion, even if it were necessary, would cost fewer than 50,000 American lives. This somber, impressive volume also offers inescapable evidence, much of it gathered from recently declassified materials, that U.S. decision-makers had a range of other concerns, among them a wish to gain the upper hand in postwar Asia by forcing Japanese capitulation before the Soviet Union's planned declaration of war and fear of congressional investigations should the war end before the costly Manhattan Project produced demonstrable results. Immediate pressures like these, *Hiroshima's Shadow* reminds us, can all too easily obscure moral compromises—until long after the events in question are irrevocable. ◊

Venturing into Capitalism

Looking for money and ideas in all the right places. **By Herb Brody**

THE INTERNET, THE STORY GOES, SPRANG from the labs of government and military scientists who wanted a nuclear-bomb-proof communications network. The World Wide Web came from a software engineer at a quasi-governmental European physics lab. The first Web browser, Mosaic, was invented at the University of Illinois and distributed free. In short, nothing about the Web's origins would seem to make its emergence as a business medium inevitable.

Boy, did that not last long. The corporatization of the Web has proceeded rapidly, as companies set out to find gold in them thar modems—or at least to portray themselves as cutting-edge organizations. At the same time, the Web has become a meeting ground for those who want to start their own companies. A few dozen clicks through this mercantile milieu can trigger thoughts of capitalism even in the crunchy granola set.

Would-be entrepreneurs will find the Web a friendly place. First stop is the Venture Capital Resource Library (www.vfinance.com), a comprehensive and easy-to-navigate site that provides well-organized lists of venture capital firms, investment banks and accountants. You can also download a massive (5,000-word) template for a business plan. The section titled "Innovation" begins: "[I/we] have a history of innovative ideas. [List your most meaningful ideas and any new ideas you have for the future.]" Fill in the blanks, send it along and you can receive a critique from the organization's staff.

Using Alta Vista's "subject search" and zeroing in on venture capital yields dozens of sites, some for individual firms, others that link to lists of their own. (Hitting pay dirt on the Web is getting to be a longer and longer process, with the accumulation of sites that are nothing but lists of lists.) A hopeful entrepreneur will take heart at first—the mere length of the roster seems to shout, "Money here! Come and get it!" But clicking your way inside a site might cool the ardor a bit. One site issues the following discouraging message: "We receive a large number of proposals and are looking to make only a few investments. After reviewing our investment criteria, you can contact us by e-mail with your business plan or executive summary."

Some startups, of course, do make it to the first rung of the ladder of success: an initial public offering, or IPO. You can tour the successes at IPO Central (www.ipocentral.com). Browse IPOs alphabetically or by industry category, or search for a particular company. Selecting the "online services" category brings up capsule descriptions of some two dozen companies. Paying subscribers to Hoover's Online (which runs the site) can get real-time status of the stock; the rest of us have to make do with 24-hour-delayed information.

Entrepreneurship is all about matchmaking, and the Web site of the quarterly *American Venture* magazine provides an online yenta service (www.avce.com). The site lists "ventures seeking capital," divided by industry, region and amount of capital sought. Judging by this and other similar sites, there are a lot more ideas looking for funding than there are dollars looking for ideas.

The fertilizer of money works, however, only if a seed of an idea is in place. Get in the inventive frame of mind at "The Inventure Place" (www.invent.org), which bills itself as a "laboratory where you can explore your curiosity and creativity." The site includes the full text of a book called *The National Inventors Hall of Fame.* Scan through the volume's entries—from air conditioning to optical fiber to zeolite catalysts—to pay the tribute of attention to the men and women who have conceived the high-tech world we live in.

Take a swig of Tang and check out the National Aeronautics and Space Administration's TechTracS site (www.ntas.techtracs.org/), which provides links to an array of the space agency's technologies that are ripe for spinoff. Dining on government leftovers may not seem very '90s, but the site offers an impressive set of stories chronicling businesses that have taken NASA technologies and run with them. One company, for instance, makes a meat tenderness gauge with technology from the Surveyor lunar lander.

The mother of all invention sites, naturally, is the one operated by the U.S. Patent and Trademark Office (www.uspto.gov). The site's search page, at patents.uspto.gov/access/search-adv.html, lets you hunt for patents by key word. It's not a comprehensive search—for that, you have to pay a patent attorney—but it gives a quick picture of how original your idea is. Spending much of my working life on the Web, I type "web and search and algorithm" to see what brilliant ideas have been patented for improving this task. To my surprise (and dismay), only one patent appears. The word "mousetrap," still an emblem of ingenuity, turns up five entries. Navigate your way to the patent office's weekly Official Gazette at www.uspto.gov/web/offices/com/sol/og/, and browse through recent issues for listing of "Patents Available for License or Sale." Anyone out there need a "bubble popping device"? There's a man in Wheatley Heights, N.Y., you should call. TR

She'd Rather Be Fishing

Nancy Hopkins trolls for the secrets of development

LANE TURNER

Hook, line and sinker: Hopkins and the fish she has fallen for.

On a balmy day the thermostat in Nancy Hopkins' lab in the Center for Cancer Research on the MIT campus is set to a temperature that is uncomfortably warm—for humans, anyway. It's fine for the other occupants: minnow-sized striped zebra fish that populate the plastic tanks stacked against one wall. Around here, what the fish need, the fish get. Hopkins is fervent about the fish because she believes that they will repay her with something of immeasurable value: a fundamental understanding of life and disease.

Hopkins is one of a growing number of researchers who have begun using the zebra fish as a tool for studying the developmental biology of vertebrates. It is, in some ways, a departure from her scientific roots. Hopkins grew up professionally along with the field of molecular biology, eventually learning the ways of viruses in an effort to uncover the genetic underpinnings of cancer. Now she has traded in viruses for fish—an exchange that reflects her enthusiasm for genetics and for being part of the early stages of a new discipline.

While most zebra-fish researchers are searching for a handful of genes important to particular organs or systems, Hopkins' team plans to pinpoint 2,400 of them—enough to build an entire animal. The project is ambitious, but Hopkins is no stranger to daring science. Her first mentor was the audacious co-discoverer of the structure of DNA, James Watson. Since her days as an undergraduate in Watson's classroom and as a researcher in his labs, Hopkins has kept what she calls "impeccable scientific company," working side by side with some of biology's most influential players. Hopkins reminisced about the early days of DNA with *TR* Associate Editor Rebecca Zacks, and looked ahead to an extraordinary fishing expedition.

You were involved with molecular biology at its very early stages—was that more accident or design?

More age, I think. I was old enough to be there at the right time. I came in in 1963, 10 years after the structure of DNA was determined, and the genetic code was still being cracked. People were still trying to figure out what DNA triplet coded for which amino acid, and Jim Watson would come rushing into class waving triplets. At that time, we couldn't imagine the answers to questions like what type of gene would the first cancer gene or oncogene be. Now we know some dozens of genes that can be cancer genes, but the very first time you find one out, your whole brain somehow changes, your world changes, the way you view nature changes.

I'd seen those changes come in the early days of molecular biology every couple of years. Generally the day somebody told you their experimental result, you knew that person would win the Nobel Prize. And they did, they always did. You could tell they would because your whole way of thinking was changed by that one instant. Now the discoveries fall more into a framework that's familiar: Somebody gets another gene for another disease; it's always fantastic and sometimes it's very surprising, but it's another one, not the first one.

Why did you make the transition from viruses to zebra-fish research?

I had the feeling that the field I was in had finished this first phase that had been super exciting, and the second phase didn't fit as well in my lab. The possibility of applying genetics in the zebra-fish system—actually finding the genes that were responsible for developmental processes and for behaviors in a vertebrate animal—was something people hadn't imagined you might really be able to do. I thought it would be fun to see whether one could make that possible, I was drawn to that.

What is your lab's goal with the fish?

We have a very sharp focus, and it's very big but very simple, very clear: We just want to understand how you start with a single cell and make an animal, that's all. And we know that it is done by genes.

If you think about early development, you're really talking about two processes: one cell becoming many (cell division), and how those cells organize themselves in three-dimensional space to make such an incredibly complex thing as a hand, a face, a brain, a pancreas. When the process of cell division goes out of control it becomes the process of cancer, and when the process of cellular organization goes awry you end up with birth defects. So if you could understand how genes allow development to occur normally and abnormally, you would understand life and illness.

We know that there are about 2,400 genes that are essential to make a normal zebra-fish embryo. If we have enough resources and enough energy, we'd love to get them all. ◊

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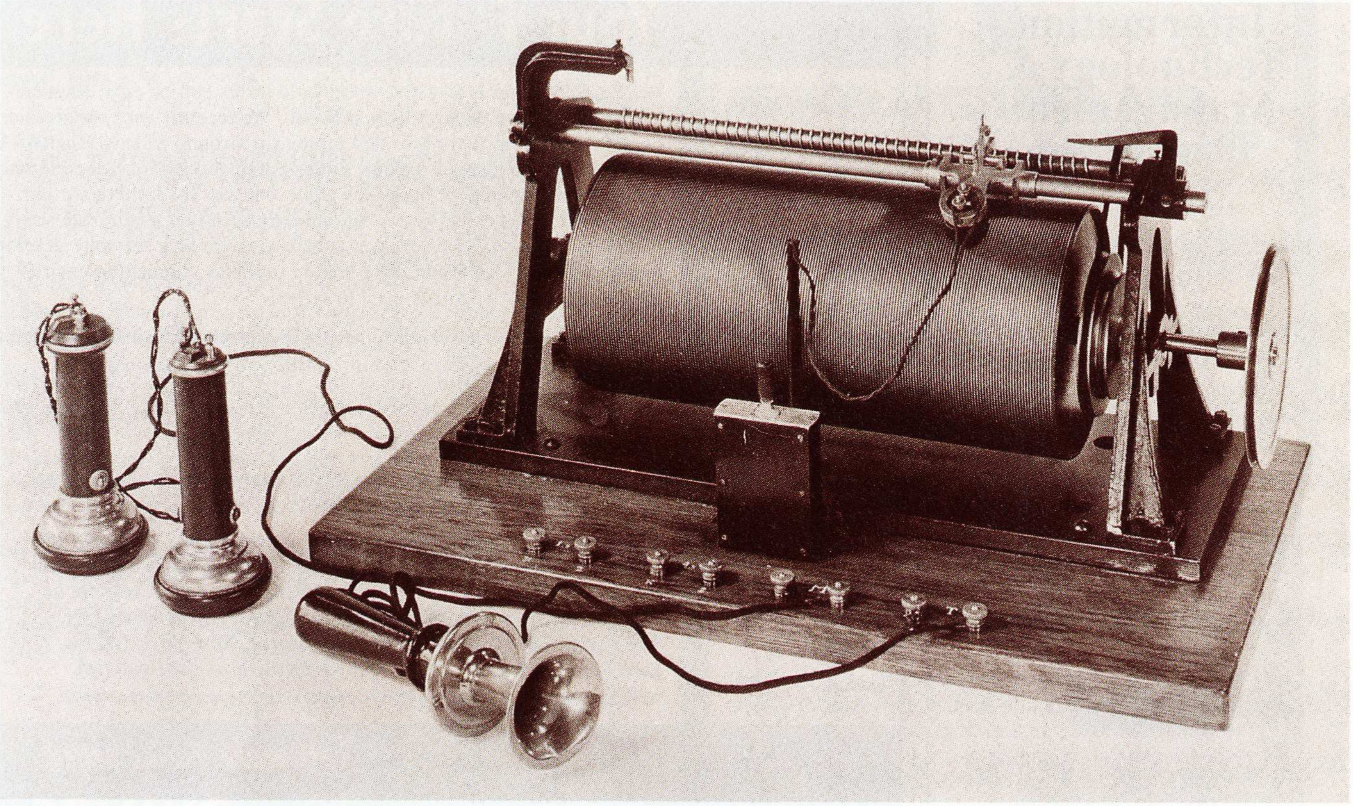

Making Steel Speak

The telegraphone sparked our magnetic memory

THIS YEAR MARKS THE CENTENNIAL OF THE INVENTION THAT brought down Richard Nixon and caused complications for Bill Clinton: magnetic recording. It was 100 years ago that Valdemar Poulsen, an engineer with the Copenhagen Telephone Company, applied for a patent on his "telegraphone," a device that recorded the human voice magnetically on a steel piano wire.

Using the 1898 model of the Poulsen telegraphone (shown above), one could capture a 45-second message on a 100-meter wire wound on a rotating cylinder; the playback sound was free from the characteristic scratching of the phonograph. Poulsen's invention earned a grand prize at the Paris Exhibition of 1900, but a half-century would pass before magnetic recording found widespread application.

There were several technical and business reasons for this delay, but foremost among them was Poulsen's choice of recording material: solid steel. In early recorders, an electromagnetic head translated the electrical signal from a microphone into a magnetic signal—a steel wire or tape passing by the head picked up a magnetic history of the sound. But steel has poor magnetic properties, so the recorders had to move several feet of steel tape or wire per second, a cumbersome and sometimes dangerous proposition. A crucial step in the evolution of magnetic recording was German chemist Fritz Pfleumer's 1927 development of a paper tape coated with powdered steel particles. This soon evolved into a plastic tape coated with particles of iron oxide and became the recording medium for AEG's "magnetophon," a superior German machine brought to the United States as booty by soldiers returning from World War II.

In 1947, the Bing Crosby radio show was recorded on a captured magnetophon, and magnetic sound recording quickly became a staple of the radio, music and motion picture industries. Magnetic data recording was an important part of the earliest electronic computers, and magnetic video recording, introduced in 1956, rapidly became important to the television industry. In its second half-century, magnetic recording in various forms, now including even ATM cards and hotel room keys, has grown to be ubiquitous in modern society.

Poulsen had originally intended his telegraphone to be used as a telephone answering machine, but for years AT&T executives opposed this application, fearing that many people would not use telephones if they thought their conversations might be recorded. Perhaps they had a point—just ask Monica Lewinsky. TR

Technology Review welcomes suggestions from readers for Trailing Edge. If yours is selected, you will win a year's subscription to *TR*. This month's winner is MIT senior lecturer James D. Livingston, author of *Driving Force: The Natural Magic of Magnets*. Send your suggestions to: Trailing Edge, *Technology Review*, MIT Building W59, Cambridge, MA 02139 or e-mail TR-trailingedge@mit.edu.

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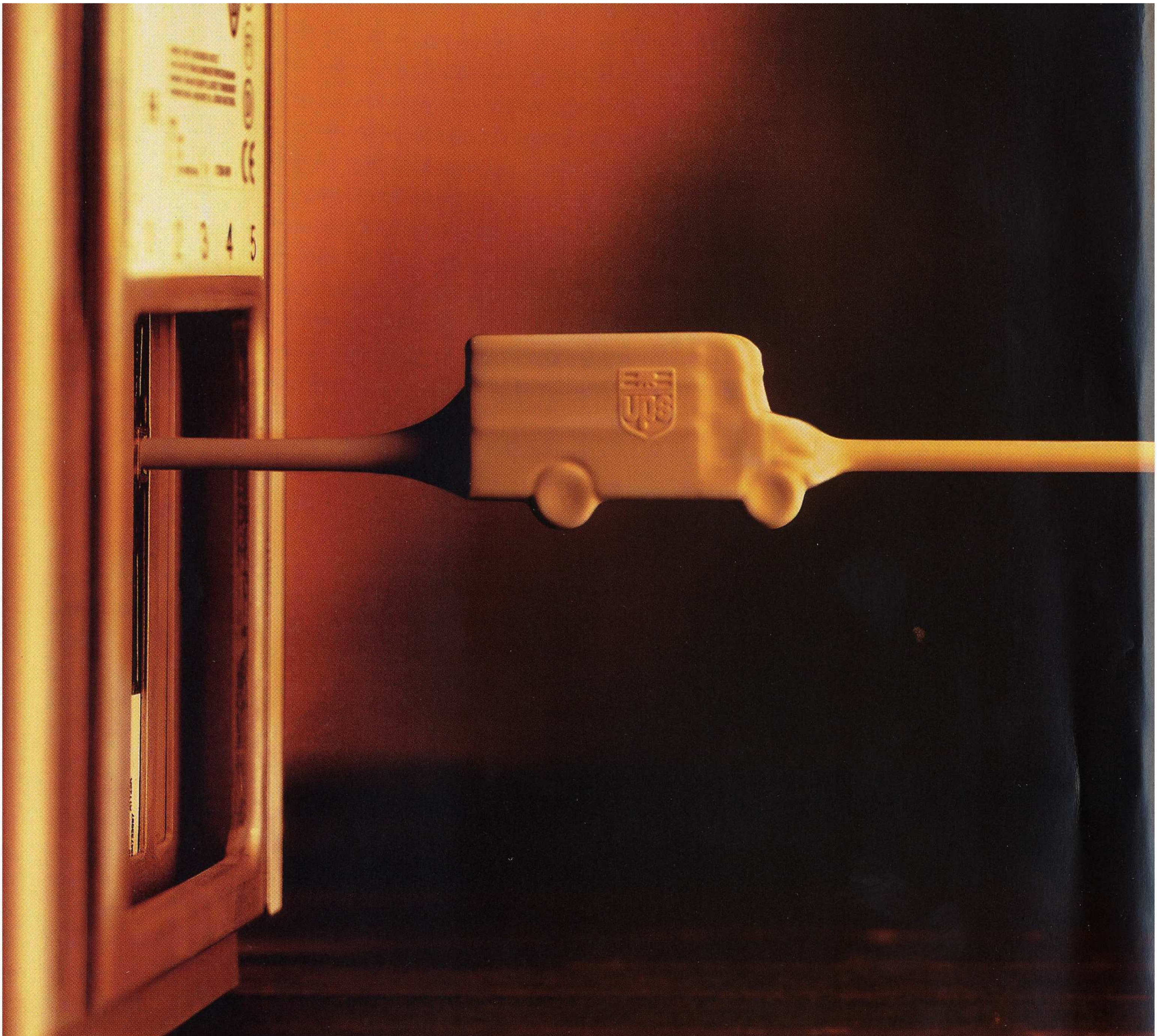

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