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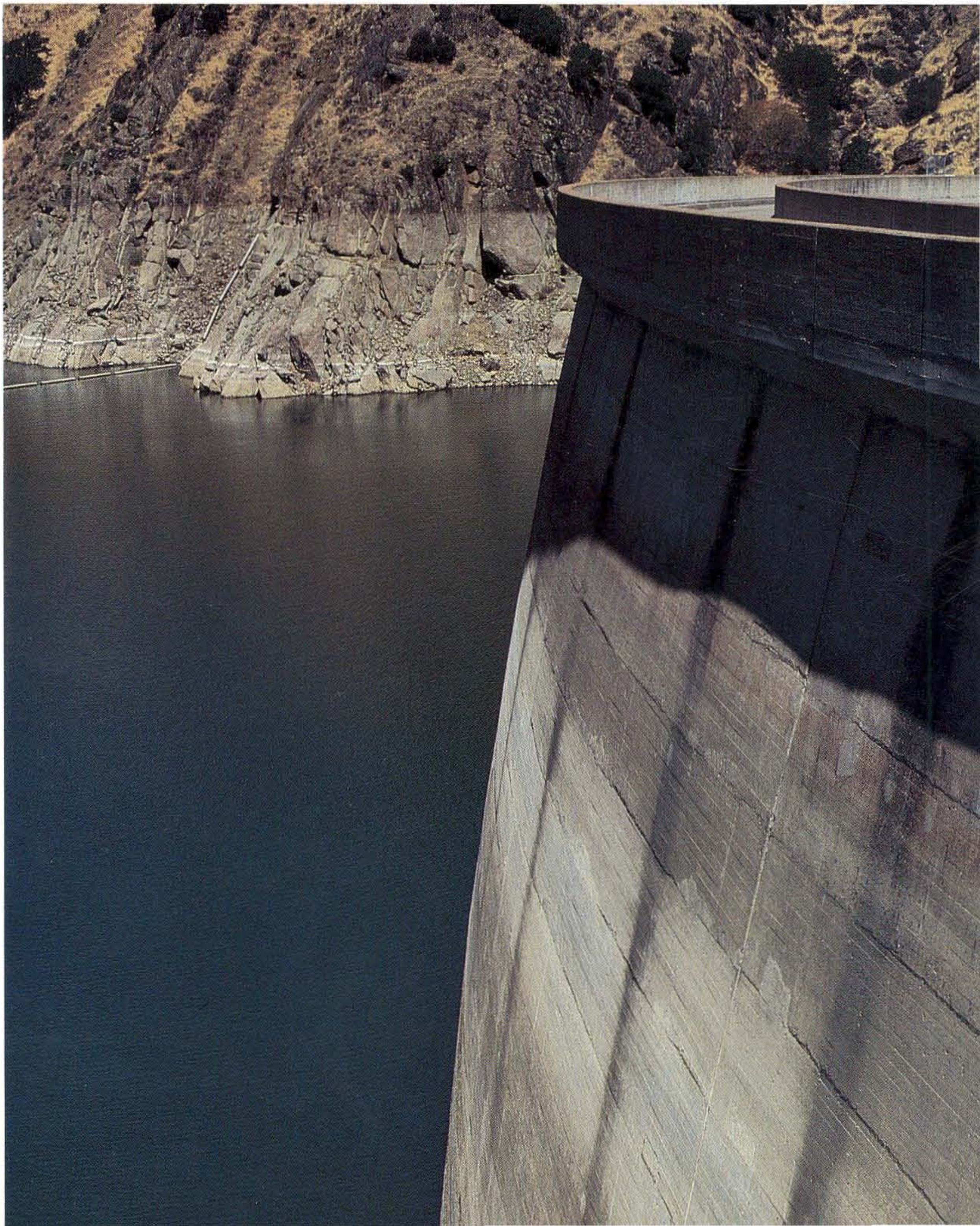

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Looking toward Irvine from Strawberry Peak in the San Bernardino Mountains, one could see smog filling the Los Angeles basin in 1975. Only the Santa Ana Mountains poke up through the smog layer in the distance. This sight is less common now.

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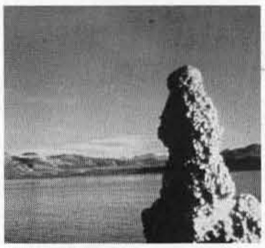

On the cover: Berryessa Reservoir, behind Monticello Dam on Putah Creek west of Davis, is very low after five years of drought. When this picture was taken in August, 1991, the reservoir was only 38 percent full. As of October, 1992, key reservoirs in northern California are as low as they were at the same time last year.

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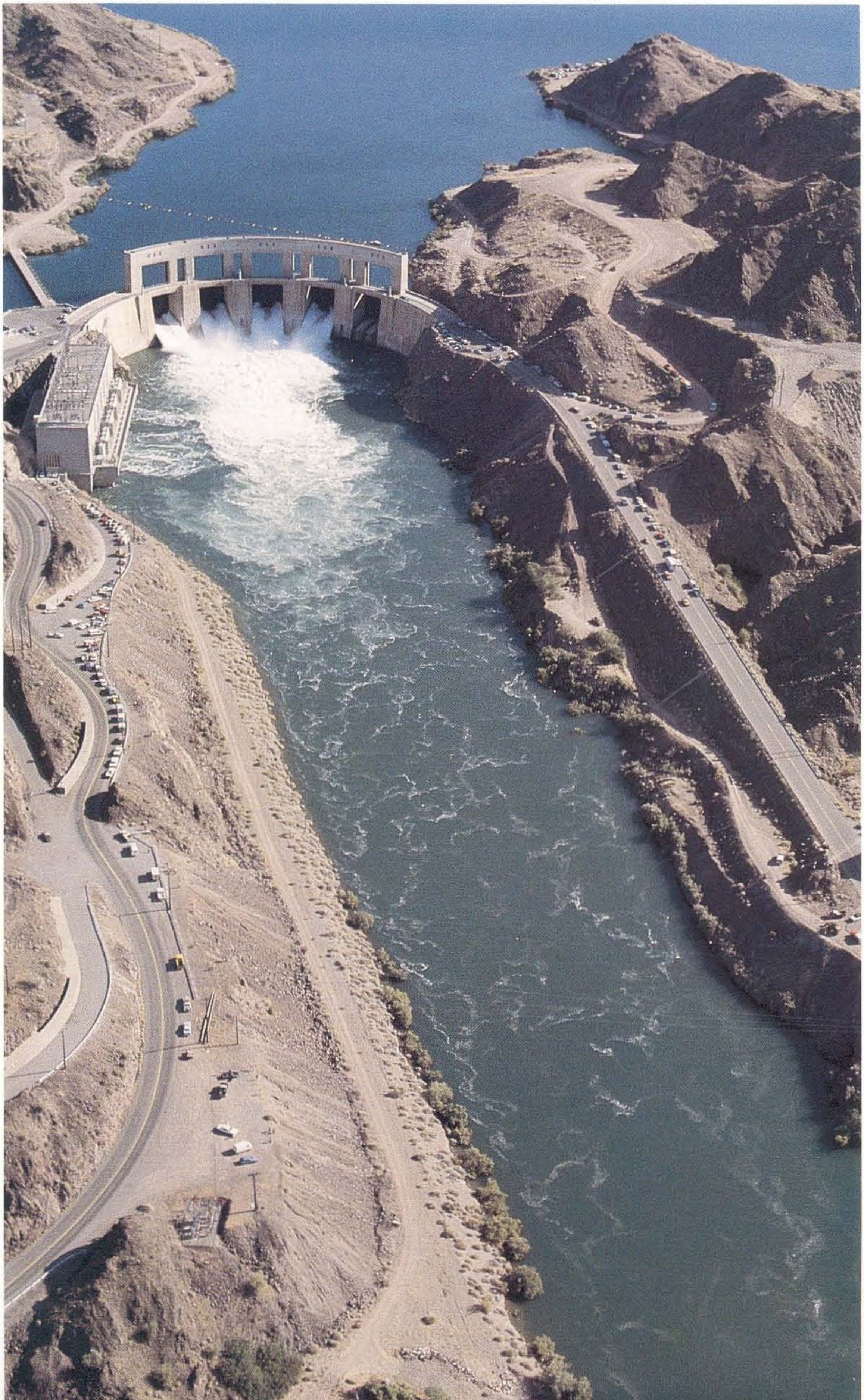


Visions of a Sustainable California

While we discuss how to make the world sustainable, here in California we still have a lot of self-examination to do.

by Norman H. Brooks

Parker Dam on the Colorado River forms Lake Havasu behind it, from which water is pumped through the Colorado River Aqueduct to thirsty Los Angeles.

California—what is our vision of a sustainable world close to home?

This is the second special issue of *E&S* on the centennial symposium *Visions of a Sustainable World* held October 27-30, 1991 at the Beckman Auditorium. In the June issue, we focused on the world view, which was covered in the opening lecture and the sessions on the first two days. This issue contains summaries of the "California Day" at the symposium.

In devoting the third day of the symposium to California, the organizing committee (James Bonner, PhD '34, professor of biology, emeritus; Sunney Chan, the Hoag Professor of Biophysical Chemistry; Murray Gell-Mann, the Millikan Professor of Theoretical Physics and Nobel laureate; Paul MacCready, MS '48, PhD '52, president of AeroVironment, Inc.; Bruce Murray, professor of planetary science; and myself) wanted to see if our large, diverse state was behaving in a sustainable way or, at least, whether we could say that the problems were not getting any worse, and no crises were looming. If California, known for its strong environmental interests and supposedly enlightened state and local governments, cannot be a sustainable piece of the world, how could we expect the world, particularly the developing world, to heed our warnings? As Provost Paul Jennings put it in his introduction to the day's sessions: "We're looking at it from the point of view that the solution of local and regional problems is an essential ingredient to the solution of global problems. And California is closer to the future than many other places. California has, in many ways, led the country and the world in running up against problems of importance to this conference and in trying to solve them."

With just one day to be devoted to California's prospects for sustainability, the committee had difficult choices about what issues to cover. California has a long agenda of short- and long-term economic, social, and environmental issues. The organizers decided to discuss only a few of these problems at the symposium in order to treat them in some reasonable detail. The focus was on growth and environmental quality, the latter being an area in which Caltech's Environmental Engineering Science program and the Environmental Quality Laboratory have been very active in teaching and research, contributing to the solution of some regional problems.

The first session considered population, economic growth, and urban sprawl: California's economy ranks seventh or eighth in the world among *nations;* can we have economic growth and job growth (the longer view as a prescription for prosperity) and still manage the environment in a sustainable way? The next session concerned energy, transportation, and air quality: Is urban sprawl so increasing our need for transportation that the prospect for generally clear air has become very hazy? The third session was about water—California's white gold: Is there not enough for agriculture and urban and environmental uses, or are the problems all institutional (such as impediments to value pricing and water markets)? The final session, "Realities for a Sustainable California," convened a panel of some of

The sessions demonstrated that California is facing some of its environmental problems—air quality and water management—with significant decade-by-decade progress . . .

the day's speakers to reflect on the day's earlier sessions and other problems not yet introduced.

In the year since the symposium the list of problems has regrettably grown much longer—the news has shown us the severe urban riots, the Landers earthquake (largest in 40 years in southern California), California's worst budget crunch since the Great Depression, the continuing downsizing of the aerospace industry, soaring unemployment (the rate of more than 10 percent is now far above the national rate), growing poverty in an increasingly two-class society, crises in school funding and educational performance, health care costing more but bypassing a growing fraction of our population, and no significant break in the longest drought in California's history. Before this past year, the seeds of these problems were all there, but they sprouted faster than expected.

In preparing this issue of *E&S* we decided to include some reaction to the events of the past year, rather than just summarizing the sessions presented in October 1991. In particular the two authored articles appearing in this issue have been updated by the speakers—Bruce Cain's talk about politics and demographics, and Roger Noll's on economic growth. In the summaries we have also mentioned recent relevant events, such as the passage and signing of the new Omnibus Water Act sponsored by Sen. Bill Bradley of New Jersey, which will for the first time make federal water available for water marketing and for urban and environmental uses in addition to agriculture.

The sessions demonstrated that California is facing some of its environmental problems—air quality and water management—with significant decade-by-decade progress, with the expectation that incremental solutions can lead the way to gradual improvements in the quality of the air and water environments. But unchecked incremental growth and development, along with social problems, might cancel environmental progress in the long run.

While we discuss how to make the world sustainable, here in California we still have a lot of self-examination to do. In the past California has been a leader with innovations to improve the quality of the environment (for example, the first emission- control standards for automobiles), and perhaps with enough foresight we can set a good example on the way toward sustainability.

Norman Brooks (PhD '54) is the James Irvine Professor of Environmental and Civil Engineering and executive officer for Environmental Engineering Science.

Acknowledgements

A number of sponsors helped Caltech celebrate its centennial with the *Visions of a Sustainable World* symposium. They included the Boone Family Trust, the Chevron Companies, the James Irvine Foundation, the Charles A. Lindbergh Fund, and the Lord Corporation. At the closing ceremony Sunney Chan, chair of the centennial steering committee as well as of the symposium planning committee, thanked the sponsors' representatives for their generous support and invited each of them to make brief comments.

Lynda Fetter of the Boone Family Trust spoke of her family's decision to help fund the symposium: "The reasons we wanted to do this are obvious. We have three sons. We're very, very interested and concerned about the world for them and for their children."

Paul MacCready read a statement from Chevron that said in part: "We at Chevron are struggling with many of the same issues, but we have made a start toward change, and you can help us with the challenges ahead. . . . Our hope is that conferences like this one can help move us beyond rhetoric toward productive problem solving on these important issues."

MacCready also spoke on behalf of the Lindbergh Fund, created after Charles Lindbergh's death by friends who had understood his message that "the human future depends on our ability to combine the knowledge of science with the wisdom of wildness. . . .We are delighted to help support this conference inasmuch as the conference and the Lindbergh Fund have the same mission: to get us to focus on the challenge of defining a desirable, sustainable future and then planning how to achieve it."

Donald Alstadt, chairman of the board of the Lord Corporation and a longtime friend of Caltech, ended his remarks paraphrasing Yeats, that "we must encourage the best to act with courageous conviction, and in some way quiet those who are full of nothing but passionate intensity. Thank you for allowing us to participate."

Chan himself spoke for the Irvine Foundation, explaining that it particularly wanted to support the California day because of its "dedication to enhancing the socioeconomic and physical quality of life throughout California and enriching the state's intellectual and cultural environment."

Population Trends: Challenges to State and Local Government

by **Bruce E. Cain**

There are actually two different types of population growth occurring in California, each presenting different challenges to California's institutions.

The spectacular facts of California's growth are well documented. Between 1980 and 1990, California grew at approximately two times the national growth rate, or about 2.5 percent per annum. About half of that growth was from domestic and foreign migration. It has changed the racial and ethnic mix of California in substantial ways. The state's population is currently 25 percent Latino, 57 percent non-Hispanic white, 10 percent Asian, and is projected to increase to approximately 30 percent Latino and 12.7 percent Asian by the year 2000 if the current trends hold. The African-American population is expected to remain stable at about 8 percent.

Inevitably, these changes are going to challenge California's political institutions in important ways. There are actually two different types of population growth occurring in California, each presenting different challenges to California's institutions. The first is immigrant, inner-city growth. The political challenge of this type of growth is partly one of overloading California's infrastructure, but primarily one of incorporating new immigrants into the mainstream culture. The second kind of growth is suburban, white, and middle class. It has little to do with the strains of social incorporation, but it has severely burdened the capacities of California's infrastructure—that is, such things as roads, schools, water, and so on.

The first type of growth, that due to migration, has been substantial. In the last decade 3.3 million people have been added to California due to migration alone. Two-thirds of them have come fron foreign nations, and approximately one-third from other parts of the United States. Foreign immigrants consist of a legal component of approximately 1.67 million people and a harder-to-count undocumented component in the range of a million or so, most of whom are Latino. In addition, the nonwhite population has increased as a result of net births over deaths. This type of growth has placed a relatively high demand on the health-care system, and particularly, hospital emergency services. It has also put a substantial demand on the educational system, both in terms of adjusting the curriculum to the cultural needs of these new populations and in terms of the sheer volume of children attending school. Contrary to popular opinion and the image that proponents of Prop 165 tried to convey in the 1992 election, it has not put tremendous strains on the welfare system, even though there are some exceptions. In particular, some of the Vietnamese and Cambodian refugees from Southeast Asia who came to the United States for political rather than economic reasons have become dependent on welfare, but that is not generally true of the Latino or other Asian communities. Ironically, the nonwhite immigrant growth conforms to the rational planner's ideals to a greater degree than white suburban growth, because it increases the density of urban areas, which helps on the margin to decrease the aggregate amount of commuting by placing people's residences closer to their places of work.

The distinctive challenge of foreign immigration is incorporation. Only a third of the legal immigrants, let alone the undocumented, eventually become citizens. One consequence of this

Los Angeles street scene.

California in future decades is going to have to adjust the way it elects representatives at all levels to ensure more proportionate representation of its racial and ethnic minorities.

is that there is a big gap in California between political representatives and the percent of the nonwhite population as compared to the percent of nonwhite voters. For example, in the 1990 Feinstein-Wilson race for governor, approximately 9 percent of the voters were Latino compared to 25 percent of the population. This political underrepresentation has given rise to a number of struggles over the way in which we do business at the city, county, and state levels. Suffice it to say that, with the beefing up of the Voting Rights Act, California in future decades is going to have to adjust the way it elects representatives at all levels to ensure more proportionate representation of its racial and ethnic minorities. Along the way, California may in the future have to abandon its Progressive-era institutions such as at-large elections and city-manager forms of government.

It may also lead to reform of the initiative process some time in the future. It is more than a little ironic that at a time when the legislature is electing increasing numbers of minorities in carefully crafted districts that California is increasingly doing business by initiative and shifting power out of the hands of the legislature into the executive branch as a result of term limits.

These phenomena are connected. The initiative is in essence an at-large election in which the state's median voter prevails. Since districts are drawn on the basis of population and respect racial and ethnic neighborhoods, the policies produced by the legislature and the policies produced by the initiative will not be the same. Due to the minority-representation gap (that is, the minority share of the electorate being substantially lower than its share of the population), minority voices are underrepresented in initiative outcomes. The problem of minority dilution combined with a host of initiative abuses (that is, paid signature gatherers, special-interest capture, sloppy craftsmanship, initiative overload, voter ignorance, appallingly shallow initiative campaigns) will inevitably lead to some initiative reform in the future.

Turning toward nonimmigrant growth, a little under a million migrants came into California from other states. Half of them were non-Hispanic whites, coming primarily from the states of Texas, Arizona, and Colorado. Much of this growth is suburban, occurring in counties such as San Bernardino, Riverside, San Diego, Santa Clara, Contra Costa, and Sacramento. This kind of growth, of course, poses far fewer cultural challenges—the children of white suburban migrants watch MTV, eat at McDonald's, wear surfer clothes, own roller blades, and do all the things that are part of our California "culture." It also has less implication for the demand for social services since these migrants are even less likely to use welfare, to need bilingual education, etc., than the rest of the population.

Nonetheless, domestic migrants place a strain on California's government and infrastructure in several ways. First, white suburban migrants create enormous demand for the existing housing stock. Nonwhite immigrants who move into inner-city areas find inventive ways to use existing housing stock, occupying garages and

It may well be the case that the existing structure of California government with state, county, and local government and special districts is an anachronism.

crowding into small apartments. But white suburban migrants require a detached home with appropriate acreage and suitable amenities. This causes high housing prices and enormous congestion on the freeways. The experience here in Pasadena with the 210 freeway is parallel to that of the 101 in Santa Clara or the 24 in Contra Costa. The outward expansion of the low-density suburbs and the separation of places of residence from places of work increasingly congests the roads. In the Bay Area, 34 communities have a net inflow of traffic during working hours whereas 128 communities have a net outflow. In addition to traffic, there are other problems such as increasing air pollution and sewage.

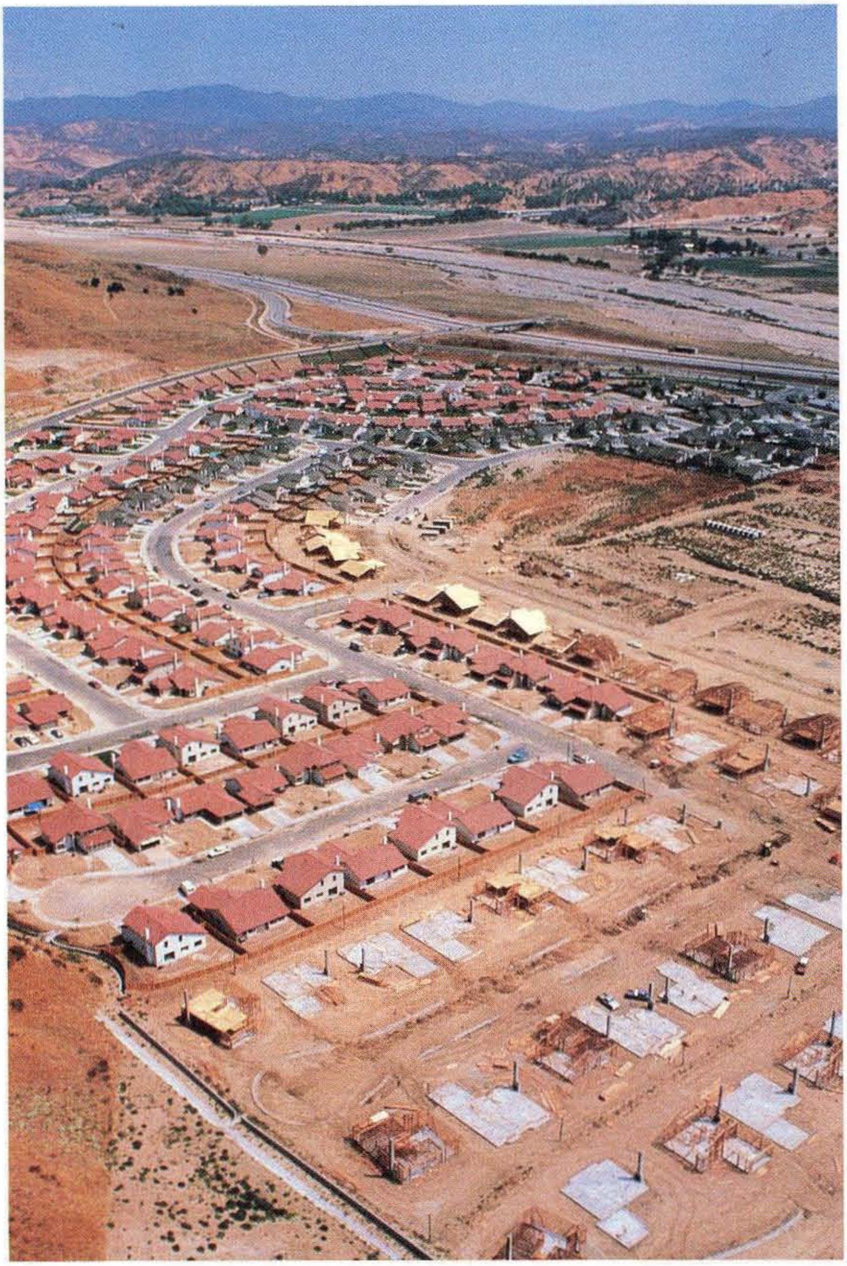
When discussing these problems, urban and regional planners tend to postulate three goals. The first is consistency: state, regional, and local planning should be noncontradictory, such that the planning goals in Walnut Creek mesh with those in Lafayette, or those in Pomona with those in Pasadena. A second goal is concurrency; that is, new development and new infrastructure should be brought in at the same time in order to avoid situations of growth without the supporting infrastructure. And the third one is compactness; suburban sprawl can be controlled by filling in urban areas and increasing urban density. Some of my Berkeley colleagues refer to this as the three C's: consistency, concurrency, and compactness. The challenge is how to realize the three C's given the tradition of unbridled entrepreneurial growth and an extremely fractured local governmental structure. In the Bay Area alone there are 9 counties, 97 municipalities, and more than 700 special districts, some of them belonging to the county and some of them belonging to cities. Needless to say, planning coordination is a problem when you have that much governmental fractionalization. There is a movement in the state now to consider proposals that will somehow put a rational structure on local and county government in order to deal with the problems of growth management. Bay Vision 2020 recently issued a report that called for an appointed regional government to set standards for and constraints upon development. This new regional government would not issue detailed plans, but it would have a veto power over any plans or projects that were developed in its area, along with sanctions to enforce its decisions. In addition, this new governmental body would have jurisdiction over many areas that are currently controlled by cities, counties, and special districts. For example, jobs and housing proximity, urban open-space provisions, the infilling of inner-city areas, the provision of affordable housing, guaranteeing high-quality water and air, transportation, the siting of new airports, and perhaps even regional tax sharing would fall under this new form of government.

It may well be the case that the existing structure of California government with state, county, and local government and special districts is an anachronism. As the demands of growth accelerate, old structures may not be adequate to deal with the problems of ever-expanding regions. There is a lively debate as to which is the better solution: a centralized, hierarchial regional government, or economic incentives plus a system of regional governance using existing multilateral and bilateral commitments between local agencies.

Apart from the issue of structure, there is the issue of consensus. If you impose regional structure where there is no consensus about growth management, then instead of growth management, there is only growth regulation leading to endless litigation. Growth management plans will not be implemented in a timely fashion, and there will be endless lawsuits over specific planning decisions. A recent study by two Berkeley professors, Marty Landau and Randy Hamilton, looked at the Land Conservation and Development Commission in Oregon and the State Land Planning Agency in Florida, and found that in both cases there were numerous problems stemming from the lack of underlying consensus. In Oregon, 90 percent of the plans that were produced by the 278 local jurisdictions were rejected on first submission, and a number of the jurisdictions have still not developed a growth plan that was acceptable to the agency.

In California, there is no consensus about growth management. There are people who feel very strongly that we can not have continued uncontrolled growth, but there are many others, particularly in minority and low-income areas, who believe that closing off growth could have serious implications for the economic welfare of the state and for the job opportunities of their citizens.

The LA suburbs keep expanding—here near Valencia.



I am convinced that growth management will be a major issue in California for decades to come. As yet, however, growth management has not been a major issue in statewide campaigns. Many people thought it would be important in the Feinstein-Wilson race for governor, but for a variety of reasons it took a back seat to discussions of taxes and crime during the 1990 election. The same is true of the recent 1992 election. But at the city and county levels, growth development politics have been and will continue to be central for years to come. If we ask the question, "Can we envision a California with no growth?" my answer would be, "No, I do not think we can." The best that we can hope for is some sort of managed or limited growth. Growth for California has historically been the device that allows us to avoid a lot of very critical choices that we might otherwise have to make. When the pie isn't expanding, it forces us to make difficult trade-offs between different kinds of programs and different ways of paying for them. I do not think that California is ready to do that, although it inevitably will have to. I would urge that, as we think about growth management, we remember that building a consensus about growth management goals is as important as setting up a structure to implement them, and second, that the current political reality is that growth has historically been an important pillar of California government. If we take it away abruptly, we may find that a lot of things start crumbling. □

Bruce Cain has been professor of political science and associate director of the Institute of Governmental Studies at the University of California at Berkeley since 1989. From 1976 until that time he was a member of Caltech's political science faculty. His BA is from Bowdoin College (1970) amd PhD from Harvard (1976); he was a Rhodes Scholar at Trinity College, Oxford (1970-72).

Trends in California's Economy: Implications for the Future

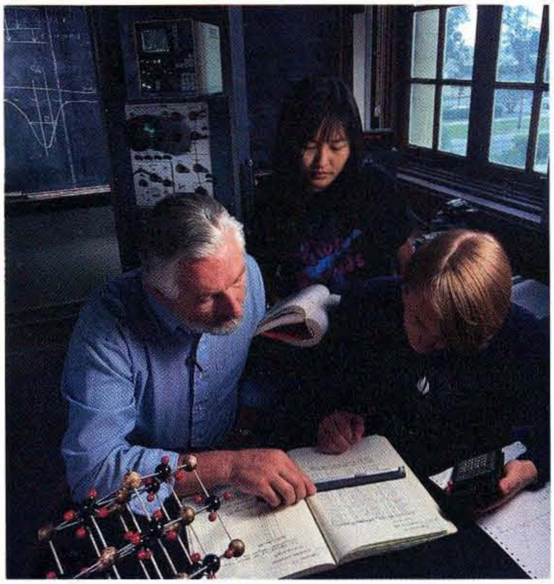
by Roger G. Noll

My aim is to outline a strategic plan for California, much as an innovative company in a high-technology industry would have a long-term business plan.

Everything important in American life is captured in our most influential cultural institution, the television commercial. In contemplating my assignment for this august event, the television commercial that came to mind was the beer advertisement in which an old codger, sitting in a 19th-century western bar, is listening to a conversation about the future. Finally, he offers his insights to a highly skeptical audience: "One hundred years from today, men will walk on the moon and only little girls will ride horses." I cannot hope to offer any insights about the future of California that are either as accurate or as compelling as the old codger's forecast. I cannot predict the state of the California economy two years from now, let alone in several decades. Moreover, anyone who tried to make such a prediction would have to be either dishonest or foolish.

One of the most important features of long-term economic development everywhere, including California, is its dependence on technological change. To forecast the ways we will occupy our work and leisure time requires forecasting the successful innovations in products and production methods of the future. To forecast technological change requires denying two core aspects of the innovative process: (a) the unpredictability of both new scientific discoveries and the uses that will be made of them; and (b) the dependence of the innovative process on having a cadre of very smart, well-trained people who are left by themselves to exercise their creativity without external second guessing. To illustrate the former, consider the debate about the value of recombinant DNA research that took place in the mid-1970s. Both opponents and proponents of this innovative research method made forecasts of its consequences. The former predicted deadly new organisms that would upset the ecosystem and perhaps bring an incurable human pandemic, and the latter forecast new miracle cures for cancer and other diseases. In reality, the first major practically significant results were not emphasized by either side—the development of fruits and vegetables with longer shelf lives that can be picked when ripe. As an example of the latter, consider the forecast in 1950 by an executive of the then-leading computer company that the ultimate total world demand for computers was likely to be under one hundred.

Because long-term economic development depends upon a loosely managed, unpredictable process, it cannot, in principle, be forecast. This unpredictability of the future makes the job of an economist at a visions conference especially difficult. Consequently, I have adopted a more modest goal than forecasting the future of the California economy. Instead, my aim is to outline a strategic plan for California, much as an innovative company in a high-technology industry would have a long-term business plan. Specifically, a strategic plan has three elements. The first is an honest assessment of capabilities; in this case, what are California's strengths and assets? The second is an assessment of the opportunities for the future, based on the core values (not the specific tastes and desires) that people are likely to have in their future. The third is an identification of the commonalities in the first two assessments, and a coherent



Don Skelton, an engineer in Caltech's Division of Physics, Mathematics, and Astronomy, works on a problem with two students. California's higher educational system is the strongest in the world.

set of actions to take advantage of them.

In the context of this conference, the assets and opportunities of California are largely determined by the constraints placed upon the state's development by the environment, natural resources, and population growth. In addressing the relationships between resources and growth, I will organize my thoughts around the issue of sustainability: how many people can live in California indefinitely at a contemporary middle-class standard of living? In this context, the standard of living is defined in the economist's (not the accountant's) sense, and so incorporates people's personal monetary measures of nonmarketed aspects of the quality of life, such as the value of a cleaner environment. My principal conclusion is that the sustainable level of per capita income in California is high—probably quite a bit above per capita income today. The problem facing California is not that it faces some sort of Malthusian deprivation due to its resource constraints in relation to its population. But, California is by no means guaranteed to succeed in attaining its sustainable level of economic well being. The problem has to do with our strategic plan—our ability to organize ourselves in an effective way to make the best use of the resources and other advantages that we possess.

The value of focusing on the sustainability question is that it identifies the challenges that our resource base will force us to face. To sustain a high standard of living in the face of a finite resource base will require transitions in the economy and the way we live our lives—but not, on balance, a significant sacrifice in our welfare unless we mismanage our assets.

The beginning of a strategic plan is an assessment of assets, and here California looks very strong. Much recent research in economics demonstrates that an area's historical economic base is an important factor in determining its future. California benefits from being at the center of the industries and technologies that are most likely to be the fastest growing in the next decade or two, notably biotechnology and microelectronics. In addition, it benefits from having the strongest higher educational system in the world. In recent years, it has become fashionable to attack universities as irrelevant and excessively expensive, and to deny that they make any contribution to a nation's economic welfare. Although universities do tend to be poorly managed from a business perspective, this view is, nonetheless, poppycock. American universities are universally recognized as the best in the world, and all of our leading economic competitors send most of their best students to the U.S. for some part of their training (usually as graduate students and postdoctoral fellows). University education happens to be one product of the U.S. that is highly successful in foreign sales, largely because elsewhere in the world the importance of education and research, especially in science and engineering, in long-run economic growth is uncontroversial. Recent economics research finds that American companies still lead the world in product innovations and radical process innovations, and that the U.S. has the highest rate of return to investment in basic research. These strong performance indicators are plausibly tied to the unique feature of American higher education—it links education and research, and teaches students how to work independently and creatively. Moreover, research on firm-location decisions reveals that high technology companies prefer to locate their research facilities near great universities. The history of the Silicon Valley illustrates this principle. It was started on the Stanford campus by Stanford faculty and alumni, and even today many of the biggest Silicon Valley companies—Hewlett-Packard, Syntex, Varian, etc.—occupy Stanford land. California's universities rank at the top in science and engineering education, and so give the state a significant advantage for the future—assuming that these universities survive the current wave of public disinvestment in both Washington and Sacramento.

California's third asset is locational. California is the primary point of contact between the United States and the rapidly growing nations of the Far East. Not only is it physically closest to these nations, but it is culturally the closest as well, owing to the relatively large number of Asians who live in California. Indeed, these two factors have led companies from the Far East to make significant investments in California. Whereas some fear international ownership of California industries, it has two very positive features. The first is that it makes up for the dangerously low savings and investment rates in the U.S. We simply are not investing enough in the future to retain a strong, internationally competitive economy. Without investments from abroad, the future of the country would be far more bleak. The second is the fact that these investments represent a commitment of these dynamic Asian companies to the future welfare of California. Investing in a nation undergoing Malthusian decline is not an attractive proposition. Far better to invest in a community that will be wealthy enough to buy your VCRs, TVs, autos, and other consumer products. The heavy investment by Japanese and other Asian companies in California is an important signal that people who have a longer time horizon than we do regard us as having an attractive future.

A similar natural advantage arises from the North American Free Trade Agreement. Greater economic integration with Mexico gives California a natural advantage that is similar to its advantages with the Far East. By location and culture California is best placed to be a focal point of economic relations with Mexico. In the 21st century, north-south trade in the Americas is likely to be every bit as important as trade with the Far East is today. Integration of complex manufacturing processes, where less skilled, more routinized and lower paying tasks are performed in Mexico and more complex, better paid tasks in the U.S., is already arising in California and Texas in connection with the *maquiladores* projects along the Mexican border, and will only be further encouraged by NAFTA.

California's universities rank at the top in science and engineering education, and so give the state a significant advantage for the future.

California's cultural advantages with respect to Asia and Latin America point to another asset for the state. Whereas racial and ethnic conflict is certainly a problem in California, it is less of a problem than nearly everywhere else. California is not only racially and ethnically diverse, it is also less segregated than nearly every other state and nation. Whereas the problems of racial and economic isolation in black and Latino ghettos is severe, nonetheless the extent of integration in middle-class neighborhoods, and especially in higher education, is great. The advantage inhering in this is not just that we stand some chance of solving the problems of our own divisions, but—probably more important for our economic future—California businesses are advantaged in dealing effectively with businesses in other countries because they are more likely to employ people who understand foreign cultures (and speak the language).

Thus, in surveying these assets, the state is well placed to succeed in the 21st century. That leaves the nature of our future left largely to the circumstances surrounding the last major asset—the natural resource base of the state. California is generally resource rich—with a couple of exceptions I will discuss below. For example, consider the effect on California of an edict to switch energy use in the state so that it relied exclusively on renewables. If the switch had to be immediate, the transition would be excruciatingly painful, because a massive investment would have to be made in energy conversion devices, largely from hydrocarbon fuels to electricity from renewable resources like photovoltaics, wind power, geothermal power, and hydroelectric generation. But in California these resources are ample to provide all current energy uses and then some. The main effect would be the cost, but even this would not be Draconian. Renewable energy is less than twice as expensive as energy from fossil fuels—and the difference is less still if one takes into account the environmental costs of fuel burning.

The most important resource constraints in California are water and air. California is an arid state, but it has plenty of water—if the water is managed sensibly. California's water problem arises not from excessive urban use—these consumers take less than 15 percent of California's supply. The problem is excessively wasteful agricultural use, such as growing water-intensive crops like alfalfa in the California desert. Many farmers pay only a few dollars per acre-foot for water, while urban businesses and residences pay $200. If farmers could sell their water to the cities, and grow crops that require less water, they could be economically better off, farming would not decline, and the state would have ample water not only for cities but for restoring inland water quality. Moreover, more efficient water use would actually increase economic welfare, replacing the production of many crops in surplus (and so valueless) with far more highly valued economic activities. In this case, a more sustainable resource policy actually increases living standards.

In the southwestern corner of California, air is a severely overused resource. Los Angeles has the worst air quality in the nation, and San Diego is sliding into a severe problem. But again, the problem has more to do with the way we manage the resource than with a fundamental conflict between living standards and air quality. Thus far, policy in California has had two main themes: (l) beat hard on auto emissions through emissions standards on new vehicles, but do next to nothing to encourage less driving, the retirement of old autos, or, more generally, the use of the least polluting models and types of cars; and (2) reduce emissions from stationary sources, but do not risk doing economic harm to any industry. The second strategy is partly the fault of the federal Clean Air Act, but it is also the fault of state policy —which is to protect small businesses and polluting industries against policies that might cause them to relocate. As an illustration of how our problems are in large measure of our own doing, California is busily undertaking policies that actually encourage the expansion of electric generation facilities inside Los Angeles and San Diego that burn hydrocarbon fuels and that are a significant contributor to air pollution. Why? Because it is almost impossible to build new generation facilities anywhere (even places that have no air pollution problem), expanding existing facilities is often the only viable option, even though the environmental costs of expanding facilities in Los Angeles vastly exceeds the environmental costs of locating new facilities in the desert.

Because it is almost impossible to build new generation facilities anywhere. . ., expanding existing facilities is often the only viable option.

Water, air, and eventually other natural resources all require economically sensible management to achieve a sustainable economy. To understand how to develop these policies requires making good use of simple economics. As Alfred Kahn once said, in some circumstances a "tyranny of small decisions" causes all to be worse off, as best exemplified by Garrett Hardin's "tragedy of the commons." From one person's point of view, the best decision regarding, say, a fishery may be to catch as many fish as possible; however, if all fishermen follow this strategy, all can suffer from a reduction in the fish population. The tragedy of the commons arises not because people are evil, misguided, or shortsighted, but because no individual adds significantly to the problem of overuse of the natural environment. Because a single person's contribution to the problem is small and mostly affects anonymous others, it is simply not taken into account in choosing individual actions. But collectively, when fully informed, people perceive that their individual best interests are to agree to curtail use of the commons, and embark on a cooperative plan to achieve this end.

A rational strategic plan for California must include strategies for managing the state's resources so as to cope effectively with potential commons problems. This strategic plan, if economically rational, would produce a future world that people who are fully informed would generally agree is preferred to all other possible futures. Moreover, because some resources are now so badly mismanaged—squandered for low-valued uses—the best available futures are likely to be regarded as preferable to the present as well. The barrier to constructing and adopting this plan is partly that people are not likely to be fully informed when they make these choices, and partly that the political institutions of the state may not work very effectively in developing and implementing such a plan even if people are informed.

In essence, the California strategic plan requires a transition to a fully renewable resource economy over a short period for a few resources (water and in some places air), and to a longer list of resources over the next few decades (most importantly energy). One major weakness California faces in implementing such a policy is that it is integrated into a larger world economy that wastes resources; however, this circumstance only stands in our way for a few items. Obviously, a California that is sustainable cannot possibly specialize in resource-intensive products that others produce in a nonsustainable fashion. But in some cases—energy most clearly—a significant shift to renewable resources is going to be economically efficient for everyone sometime in the not impossibly distant future, so that a movement in that direction can position California well for the economic structure of the future—including selling the technologies of renewable energy and energy efficiency. In other cases, notably water and air, California has a special problem that it must solve or face a diminished standard of living.

Thus, California can find opportunity in some of its constraints, because these opportunities mesh well with a predictable future value. In the 21st century, greater emphasis on renewability and resource efficiency is a predictable value, not because environmentalism is sure to capture the political center, but because economic necessity will demand it. California's air-pollution problem, in particular, can create a local market for less polluting energy conversion technologies, with a concomitant enhancement of the attraction of energy efficiency and renewables (because they are generally less polluting and, perhaps more importantly, can be licensed as new facilities outside the large urban centers).

Economists have developed useful ideas about how policies can ease this transition, avoiding economic shocks. Most fundamental is the notion that scarce resources ought to be appropriately priced; in California, it is nonsense to give away air and water. Markets can be created where they are now limited or banned, such as the recent movement for trading water rights and air emissions permits. Likewise, emissions-reduction credits should be available for firms that can figure out ways to control currently unregulated sources. For example, a major source of air pollution in Los Angeles is products containing volatile organic chemicals: paints, solvents, hair spray, oven cleaner, deodorant, etc. In many cases, regulations have not been imposed either out of fear that to do so would cause serious economic harm to the companies that are sources of pollution or because the air-pollution regulators lack the resources to enforce regulation of a large number of small sources. But large companies are likely to find it cheaper to pay for solving these problems than to ratchet down further their already rigorous standards.

California's problem is not that the resource constraint is so binding that we face a significant economic penalty if we move to a system that is less wasteful of resources. The problem is a lack of will to cope with the problem in an efficient manner. We have known about our water problem, and how to solve it, for at least 25 years. We have known about the dimensions of the air quality problem, and how to solve it, for at least 15 years. And, in the past few years, the cost of far less environmentally damaging energy technologies has fallen dramatically—but we have cut back on research to bring these technologies to commercial readiness, and have not adopted policies that would make environmental costs figure fully into the calculus about which technologies to use. California's strategic plan, therefore, is not at all impossible to write, nor is it one that promises a dark future. But it is one that has proven difficult to implement. In the corporate world, the failure to implement so promising a plan would lead to bankruptcy—or, before that, a takeover. Maybe we should sell the entire state to the Japanese . . .

But the nasty dark side of California's advantages is that most of the rest of the world is not so fortunate.

The rosy picture for California arises from some key strategic advantages for coping with the resource limitations facing the world in the future. Like most of North America, California is resource rich and has a low population density. But the nasty dark side of California's advantages is that most of the rest of the world is not so fortunate. The really difficult problems associated with sustainability arise in the poor, densely populated nations of the world. Suppose that California and the rest of the advanced, industrialized world succeeds in controlling its population and moving to a sustainable economy, but the remaining 80 percent of the world does not. What, then, is our ethical obligation? Do we face a moral imperative to reduce significantly our own standard of living to feed the Malthusian maw of the rest of humanity? And, if so, what form should our assistance take?

The ethical problem posed by the condition of the poor nations of the world is by no means simple. In the end, the achievement of sustainability in these countries turns on their ability to control population growth. It is difficult to make a moral case that the advanced world is obligated to provide assistance to countries that will use it in a way that merely increases the number of people living at subsistence. But even if the ethical argument favors this form of assistance, I believe that it is politically unrealistic to expect Americans to volunteer for a diminishing standard of living in order to feed the Malthusian maw. The real challenge of sustainability, then, is not in California, or even the United States. It is in controlling population in poor countries. Many reject the idea that rich countries should be telling poor countries what to do. But, the tragedy of the worldwide commons is that the sustainability of our way of living ultimately depends on the sustainability of other economies, so that we have a legitimate stake in curbing the pressures of human population on global resources. If others do not control population, California can remain sustainable at a high living standard only if the resources made available to the poor countries are insufficient to permit a continuation of rapid growth in worldwide population. Both normatively and practically, this means conditioned aid to poor countries—the active inclusion of population issues in development assistance. □

Roger Noll is the Morris M. Doyle Professor of Public Policy in the Department of Economics at Stanford University. Noll earned his BS at Caltech ('62), then went to Harvard for his PhD ('67) before returning to join the Caltech faculty. He was chairman of the Division of Humanities and Social Sciences (1978-82) and Institute Professor of Social Sciences (1982-85).

California's Growth

In addition to Bruce Cain and Roger Noll, who gave the session's principal presentations, the panel consisted of moderator John Bryson, chairman and chief executive officer of Southern California Edison; and Jane Pisano, dean of the School of Public Administration at the University of Southern California and president of the 2000 Partnership.

Population growth no longer connotes prosperity in California. It has come to mean a deteriorating quality of life.

Growth, of California's population and economy, has been the critical ingredient in the state's heretofore golden good fortune. But managing the problems that this growth has brought, and that its current decline is also bringing, is necessary in order to sustain prosperity in the future. "Surely, California has been the vision of growth," said John Bryson, in opening Session VIII. "For most of its history, Californians have looked upon growth as the engine of prosperity. Growth created jobs. It created the opportunity to expand educational and cultural horizons, to build universities, museums, concert halls, sports stadiums. And as the state's population skyrocketed, Californians stood and cheered the extraordinary movement toward inevitable victory in the seemingly endless race to become ever bigger and better."

Bryson recalled the great rejoicing during his undergraduate days at Stanford in the early sixties, when California's population passed that of New York. Also evident was a "widely felt sense of accomplishment" that California had become the largest state in the Union. "For decades California's expanding population attracted a seemingly infinite number of businesses and industries, and the economy outpaced the rest of the country year after year."

But ultimately "there was no prize for this victory," Bryson continued. Population growth no longer connotes prosperity in California. It has come to mean a deteriorating quality of life—traffic congestion, air pollution, out-of-reach home prices, too many demands on school systems—all of it directly attributable to the population growth that had served the state so well in the past. So, although new arrivals continue to pour in, many people are leaving. Bryson cited figures from the state department of finance indicating that more people in the prime-productivity years of ages 30 to 44 have left California than have moved in. Businesses are also departing. An Edison study found that about 10 percent of California's recent job losses are from company relocations. These firms cited business costs as their main reason for leaving. All told, California has lost 600,000 jobs this recession, according to Bryson.

"Dealing with the issues created by growth will require Californians to adopt a new vision and a new set of solutions to the state's extraordinarily difficult problems," said Bryson. "And it will demand, I think, a far greater degree of cooperation between the public and private sectors. Managing growth will require business to reconsider in some ways its traditional definition of success." This definition must include, he continued, a focus on enhancing the quality of life and protecting the environment. Bryson went on to describe how Southern California Edison, unique among the nation's utility companies, has proposed to reduce the carbon dioxide emissions from its power plants over the next few decades despite foreseen demand for electricity. The company is also devising energy-efficient technologies for its customers and is working on the development of nonpolluting electric transportation.

In the panel discussion and questions that followed, Jane Pisano offered a different view of a

Managing growth will require business to reconsider in some ways its traditional definition of success.

utility company's motivation to help solve local problems: they can't leave. "Utility companies and newspapers are the only industries that really *have* to be in California," according to Pisano. Due to information-age technology, "our businesses are much more highly mobile today than in the past." In addition, California's economy has been hurt by its belated shift, after the rest of the country, from a manufacturing base to a services base, she said. As for the strain population growth puts on the services and infrastructure, Pisano maintained that this is but one side of the equation. "The other side of the equation is that we haven't kept up in terms of supply. We have failed over many years in this state and the country to make the kinds of investments that are required in order to maintain our standard of living."

She also countered the optimistic forecast Roger Noll made in his talk of California's position in Pacific Rim trade by noting that California, with Mexico's cheaper labor right next door, was also well positioned to be hurt by a global labor market. "We have to be cognizant of the fact that there are real consequences for living in a global economy and an information-age society," Pisano said.

But both Noll and Bruce Cain were more sanguine than Pisano about California's proximity to Latin America, and both supported the idea of economic integration—a North American free-trade zone. "Mexico is a resource-rich country, and there's really no reason why it can't develop," said Noll. "It's not going to be particularly difficult at all for the U.S. engine of growth to pull along the southern part of the North American continent." Cain emphasized the interdependence of North American neighbors: "California's problems aren't solved simply in California." Trade relations and economic growth in the southern part of the continent would offer a partial solution to what Cain described in his talk as type-1 growth—immigration into California's inner cities. "People won't feel they have to come to the U.S. in order to have a job," said Cain.

But if they *do* come, Cain replied in answer to another question, "there's no way that California is going to be able to control its border and say, 'We're not going to grow by more than 30 million.' I think that a more sensible strategy is to think about how we can manage the growth that we're going to have to expect." No one offered any specifics, but Cain was optimistic that the American fractured, decentralized political system can cope with such a strategy. As Noll had put it earlier, "There's a built-in inefficiency to what we do, owing to the requirement to achieve political consensus. But that serves an ethical value that we hold dear—that we have a governmental system in which most of us have to agree with a policy before we pursue it." Cain suggested that sometimes the unexpected comes out of a decentralized process with people trying different approaches. "I think we just have to accept that the nature of the governmental structure is going to push policy in a certain way that will at times look inefficient, but that's not to say that that structure is incapable of performing and of accepting the challenges."

Pisano echoed "the absolute absence of a con-

Although immigration is often considered the source of California's growth problems, two-thirds of future growth in southern California will be from births to people already living here.

sensus in California," and as an example described her participation in the California Growth Management Consensus Project. "Although this group labored mightily, it was unable to come to conclusions about how to manage growth in California or how to make tradeoffs that would even lead us in that direction," she said. In a typical debate, the environmentalists, who wanted to plan "quality" economic growth only for the population that is wanted, clashed with the representatives of ethnic organizations, who interpreted this as an exclusionary attitude meaning, "I've got mine and you're too late."

No one on the panel came down on the side of no-growth, particularly in southern California. "I can't imagine a future for Los Angeles without growth," said Pisano. But, she warned, "I think that we run a very real risk in southern California, and throughout the state and the country for that matter, of a widening gap between population growth and job growth, which could lead to increased levels of unemployment." This would also mean a widening gap between rich and poor, which would, in turn, have obvious consequences in exacerbating racial and ethnic divisions within our society, she said. None of the panel went along with a suggestion that California is moving toward a Latin American model of a poorly educated lower class, a small middle class of scientists and professionals, and an even smaller rich and corrupt ruling class. Cain, in particular, although agreeing that immigration patterns make for a two-tiered economy, and condemning the power of money in our political system, said that such a comparison was far off the mark and "doesn't portray a very deep understanding of our problems in the United States."

Although immigration is often considered the source of California's growth problems, two-thirds of future growth in southern California will be from births to people already living here, according to Pisano. In answer to a question on controlling such population growth, Noll stressed the importance of opportunity as opposed to coercion. "Historically, at least, when people have been provided opportunity, they do not have extremely rapid population growth."

At the end of the session, Bryson asked each panelist to state the single thing that each would recommend to the governor and the state legislature to do in the next year to improve the prospects of California over the next decade and beyond. Noll said that "the single best policy change would be to rationalize the water-allocation system." Pisano would urge the adoption of policies more friendly to and supportive of business. And Cain thought that changing the tax structure would be the major challenge of California in the 1990s—"not simply arguing about more or less, but really looking at a more coherent way of going about paying for services in California." □

Energy, Transportation, and Air Quality

Speakers in this session were Glen Cass, professor of environmental engineering and mechanical engineering at Caltech; John Holdren, the Class of 1935 Professor of Energy at UC Berkeley; and Mary Nichols, director of the Los Angeles office of the National Resources Defense Council. The panel discussion, moderated by Roger Noll, the Doyle Centennial Professor in Public Policy at Stanford University, also included John Bryson, chairman and chief executive officer of Southern California Edison.

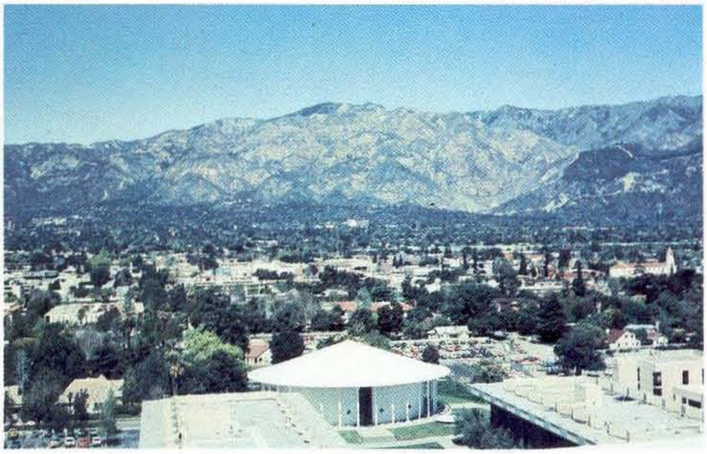
If you look at where {energy} goes, California uses a smaller percentage in industry and a much larger percentage in transport.

California's concerns about energy, transportation, and air quality of the future converge principally in the automobile. John Holdren, who spoke in general terms about the efficiency of energy production and use, pointed out that, although California has less-energy-intensive industries than the rest of the country, the state is "basically as fossil-fuel dependent as everybody else—some 83 percent of what it uses comes from fossil fuels. But if you look at where it goes, California uses a smaller percentage in industry and a much larger percentage in transport."

In her talk, Mary Nichols laid the blame for this on the state's land-use patterns. "California's urban growth has always been characterized by urban sprawl," she said. "The people who came here wanted to get away from what was perceived as the unhealthy concentration of the old-style civilizations of Europe and the eastern United States. The notion of being able to spread out and (later, after the electric streetcars were replaced by automobiles) being able to move from your problems by just going beyond the city limits to the next rural area have characterized our politics and our land-use planning from the very beginning."

The automobile's ultimate impact has been on air quality. Glen Cass discussed the local air-pollution problem in his talk, "How Can We See the Future Through All of That Smog?" He started out describing the evolution of the problem because, he said, "I think it's instructive for the future to understand how we got where we are." The air-pollution problem in southern California is extremely complex, Cass said. "It's really at least a half dozen and probably many more air-pollution problems all mixed into the same air mass. We have to be concerned with control of emissions of sulfur dioxide, carbon monoxide, an entire family of the oxides of nitrogen, hundreds of individual hydrocarbon species, not to mention reactions between the oxides of nitrogen and hydrocarbons that produce ozone, and the small particles suspended in the atmosphere that obscure visibility." To confine his talk to the time limit, Cass concentrated on the past and possible future of ozone and photochemical smog in Los Angeles, touching briefly on the problem of visibility caused by light scattering due to fine particles in the atmosphere (a situation Cass's lab figures could theoretically be cut by 40 to 50 percent—not perfect, according to Cass, but at least "the mountains would become apparent to the person on the street on a greater number of days per year").

Scientific understanding of the ozone problem is relatively well advanced, according to Cass. Sunlight acting on nitrogen dioxide gas in the atmosphere leads to ozone formation. The ratio of nitrogen dioxide to nitric oxide determines the amount of ozone, and reactive hydrocarbons increase that ratio, thereby increasing the ozone concentration. Cass and his graduate students are using mathematical simulation models of what happens in the air over southern California (taking into consideration such elements as the atmospheric chemistry, the spatial distribution of emission sources, the amount of sunlight, and wind speed and direction), dividing the area into a grid system of small air volumes that can each




From the top of Millikan Library, the peaks and canyons of the San Gabriel Mountains stand out clearly on a smog-free day, but on a smoggy summer day the mountains disappear. Visibility impacts of air pollution have been one of the focal points of Glen Cass's research group. (Photos from Susan Larson's PhD dissertation, 1988.)

be treated as a chemical reactor. They can thus calculate and predict an expected amount of ozone production, which agrees quite well with actual observations of ozone concentrations over time. They can also use models of this sort to examine the emissions allowable to achieve air-quality objectives with respect to ozone. It has been known for nearly 20 years that the maximum air-pollutant emissions that are compatible with attainment of the federal ozone air-quality goals total only a couple of hundred tons of reactive hydrocarbons per day and about 400 tons per day of oxides of nitrogen.

Attacking the ozone problem via the hydrocarbons has been the route of choice. Cass noted that "we've made incredible progress toward reducing emissions of reactive hydrocarbons in Los Angeles. From an emission rate of approximately 1 pound per day per capita in 1940, we have declined now to the point where we're emitting about 0.23 pounds per day per capita, a reduction of more than 75 percent—a tremendous accomplishment. It's worth noting that Los Angeles is approximately 30 years ahead of the rest of the United States in terms of emission control on a per capita basis."

The number of people in the air basin, however, has increased dramatically—from 3 million just before World War II to approximately 12 million now (and projected at 15 to 16 million by 2010). "Not surprisingly," according to Cass, "the effect of declining emissions per capita and an increasing number of individuals has resulted in a tug of war, and lo and behold, emissions of reactive hydrocarbons today and emissions in 1940 are substantially the same—about 1,500 to 1,600 tons a day." So we still need an order of magnitude decrease in present emissions to reach present air-quality goals.

In addition to motor vehicles, Cass pointed to a category of hydrocarbon sources that come from evaporation, not combustion—the evaporation of solvents contained in a multitude of consumer products: paints, industrial adhesives, furniture polish, dry-cleaning materials, and so on. These sources, each of which constitutes only a few percent of the overall emission inventory, come from diverse activities occurring at the personal level all over the economy, but together pour several hundred tons of hydrocarbons into the southern Californian air. Cass described these "small fugitive emitters" as "sort of a death by a thousand cuts," and was not optimistic about an easy solution to cutting off these sources.

Automobiles, however, are another story. Cass and graduate student Rob Harley used their air-quality models "to completely delete gasoline-powered motor-vehicle emissions from the atmosphere and project the effect that would have on air quality in southern California." There was a drastic improvement, but still not enough to eliminate the local ozone problem. Motor vehicle emissions control is clearly a necessary part of a solution to the problem, but it is not the whole solution. "My personal opinion," he said, "is that in the next 50 years, if not at present, it is technologically feasible to eliminate motor-vehicle emissions as a contributor to this problem." He listed a number of different ways, including gasoline-powered cars that are truly durable and

Clearly we can *control the motor vehicle. The more interesting question is whether or not we have the consistency of social purpose to carry that out.*

well maintained, cars that burn alternative fuels, and electric vehicles. He placed most of the blame for current emissions, which are actually higher than government estimates, on old, poorly maintained automobiles. One study of pre-1971 cars showed that they had 65 times the hydrocarbon-emission rate of new cars.

Even if technology permits the control of motor vehicles, said Cass, the hydrocarbon contribution of the small fugitive emitters "may mean that hydrocarbon control as the ultimate solution to the Los Angeles ozone problem can only go so far. Either we will wind up with air quality that is better than at present, but not what we would ultimately desire, or, alternatively, very serious study must be given to trying to starve the atmosphere of oxides of nitrogen. I think this is probably more feasible in a technical sense because at least we're working against a zero baseline." (Hydrocarbons also come from biological sources, which really can't be controlled.) "But clearly, we *can* control the motor vehicle," said Cass. "The more interesting question is whether or not we have the consistency of social purpose to carry that out."

Mary Nichols, whose topic was reshaping California's cities, echoed the notion of public willingness. "The issues that I'm talking about here are certainly not new. We are perhaps at the end of a long cycle, but I don't think we're raising any new questions or concerns, and the policy choices aren't really all that different from what they have been in the past. It's a question of whether we now have the political opportunities or the political will to do something about them," she said. She decried the decision-making process in multiple levels of government: "We're making decisions in a way that isn't coordinated and doesn't respond to any particular set of policies that make any internal or integrated sense."

"The tax structure that we've created for ourselves makes it nearly impossible for the people who have control over land-use decisions to do the right thing," Nichols continued. "We try to preserve the notion that land-use decisions should be made at the level of government closest to the people. Revenues from land-use development are the principal source of income for local governments to do the job of planning and governance and provide police protection and court systems and all the other things that people want from government. So we have created a tax system that penalizes local governments for allowing for greater residential development and instead rewards those that can attract the greatest amount of commercial development. But figuring out how to change that in a way that takes the incentive for bad land-use decisions away and replaces it with positive incentives to do the right thing is extraordinarily difficult to agree to." On one side are the citizen organizations, homeowners, and environmentalists, and on the other are business and landowner groups. All want the maximum amount of flexibility.

The key to good land-use decisions, and the one that environmentalists are most concerned about, is mobility—"a lifestyle that will allow people to move about in their communities"—Nichols said, and this leads to a focus on transportation. Not only is transportation responsible for 75 percent of our smog problem, but "we're beginning to develop the data to show that we're underpricing our transportation system in a serious way. We have a road system that is being used at above its capacity. At the same time, we have no mechanism for pricing access to that system that would lead people to invest in other, better alternatives. The transportation sector is one of the few areas in which the public has been willing to vote additional taxes at the state and local level."

Even though the public has seemed willing to pay for transportation improvements, Nichols maintained that "we need to look at the way we invest in transportation projects. We should try to make those investments on a basis that in the electric-utility sector is known as least-cost energy planning, in which you make investments based on *all* of the costs of achieving a particular level of energy performance, including the environmental externalities." Although government regulation and investment have been proceeding along separate tracks for several decades, Nichols thought that the "revolutionary" idea that transportation planners and air-quality planners should talk to each other had finally dawned on government officials.

John Holdren also saw energy policy as the link that would enable California "to deal with the intersection of land use, transportation patterns, and regional air pollution." But in his talk, he sought to put California "in context as it exists for the United States and for the larger world in which California has to try to fit and to prosper."

In looking at the energy problems that we have in the nineties, Holdren claimed "we are certainly not running out of energy in any global or absolute sense. There are tremendous quantities of energy resources." But he listed a number of important things that we *are* running out of: the cheapest and most accessible supplies of petroleum and natural gas and hydroelectric sites;

the regenerative capacity of biomass; the environment's capacity for effluents; public tolerance for the perceived risks of nuclear energy; and public tolerance for inequity in the distribution of energy's costs and benefits. We're also running out of money for alternatives, as well as time to adjust and steer the "very ponderous energy system" onto a new course, Holdren continued, and we're running out of the capacity to deal with the enormous complexity of the special interests. "And we're running out of, or perhaps never had, the resolve to act," he said.

Of all the environmental problems, Holdren considered that "the most intractable, the most difficult in the long run, and perhaps the most serious constraint on our energy choices for the next hundred years is the threat of climate change through accumulating greenhouse gases in the atmosphere," for which energy is about 60 percent responsible. The rich countries (about 1.2 billion people versus 4.1 billion in poor countries) use 75 percent of the industrial energy forms and two-thirds of all the energy forms and produce most of the carbon dioxide. "Of course, the poor don't plan to stay that way," said Holdren. "They plan to get rich, and most of them plan to get rich the same way we did—on a subsidy of cheap fossil fuels. And there are still enough of those around, particularly the coal, for them to make a very good try at it."

On the basis of GNP per unit of energy, the state does much better than the world as a whole or than the United States as a whole, in part because of our service industries and other relatively low-energy activities.

Narrowing down to California, Holdren pointed out that on the basis of GNP per unit of energy, the state "does much better than the world as a whole or than the United States as a whole, in part because of our service industries and other relatively low-energy activities." But California still needs to increase further the efficiency of energy use, an approach Holdren called "the cleanest, cheapest, fastest, safest, most reliable way" to address energy problems. He stressed the importance of finding cleaner and safer ways of using the energy sources we have now, since we can't simply abandon those overnight. But at the same time, "we need to begin a transition to forms of energy supply that are more sustainable in the environmental sense."

Among the kinds of technologies he saw emerging in California between the year 2000 and 2050, Holdren topped his list with fuel cells for dispersed as well as central-station electricity-generation applications and biofueled cogeneration of process heat and electricity. Further down the list come hydropower ("although there's not a great deal more of that in California that can be developed without running into very strong public opposition, which would include me, against damming the last remaining free-flowing rivers in the state"), wind, and geothermal power ("not inexhaustible and not an enormous potential for California"). Among the "sleepers—things of low probability but which could fool us all," Holdren listed advanced fission reactors, solar thermal electricity generation, and fusion, a field in which he himself works. ("None of us expect to see something you could describe as a commercial fusion reactor until 2025 or 2030; that means there's really no chance of a large impact before 2050.")

Although the federal government hasn't been doing enough to move us closer to these kinds of energy sources, Holdren said, "California is very well positioned to do a lot." Among the state's assets he included "the most progressive and informed electric utilities in the U.S." and the ones most willing to take action, the best universities, the best public-interest organizations, and the high-tech companies "that will know an opportunity when they see it. We have more good energy R&D than anyone outside of the federal government, and we have a less developed neighbor to remind us of why their situation matters, too. And we have a tradition of leading, rather than following, on energy and environment issues."

John Bryson, in opening the panel discussion, focused on regulation of those same electric utilities that Holdren had called the most progressive and informed in the country. "The question is whether or not regulated electric utilities as they traditionally exist can continue to exist in the future." Traditionally, regulation in the public interest has enabled utilities to make long-term investments with a reliable recovery of the cost. And reducing environmental impact, in particular reducing carbon dioxide emissions to minimize the potential for global warming, involves costs and choices that a utility company needs to plan for over the long term. The current climate of economic deregulation, however, said Bryson, in which customers may be able to choose where to go for their electric supply, puts the now regulated utilities in a dilemma. "The problem is," he said, "that there is simply no agreement at the current time about the steps that might reasonably be taken now to protect the environment." He emphasized that "we have an enormous social consensus that the environment is worth giving more attention to, paying more for than we have traditionally paid."

But Bryson did not approve of regulation for regulation's sake, describing command-and-control environmental regulation for improving air quality as "blunt, crude, and cost ineffective," with no discretion left to utilities or others in the

Right: At SCE's Huntington Beach electricity-generating plant, which burns oil and gas, emissions control may be managed by tradable permits in the future. Below: This view under the hood of an electric car may be a common sight by the year 2020.

private sector "to use their best engineering ingenuity and their understanding of costs in their own areas to come to desired solutions. With regulatory micromanagement we would end up paying vastly more per unit, for example, of nitrogen oxide reduction in the Los Angeles basin than under a market-based system of regulation that provided incentives."

Bryson also addressed the role of technology. "At Southern California Edison we are seeking to direct our research dollars into technology advances that can contribute significantly to solving energy and air-quality problems. As a utility with customers across the commercial base in greater Los Angeles, we have some direct connection to the problems businesses face with respect to meeting air-quality standards. And one of the things that we're initially encouraged by is the extent to which our work in the development of or identification of advanced electric technologies can contribute to the solution of some of these problems, while enhancing productivity at the same time."

Most of the question session veered back to the automobile, as one symposium participant observed that he was usually alone on the shuttle bus between the hotel and Caltech and hoped, probably in vain, that the others had all walked. "How can we possibly hope to change others' behavior if we can't change our own?" Panel moderator Roger Noll owned up to driving his own "gas-guzzling dinosaur" but tactfully did not press the question on the rest of the panel. But if we're not going to get out of our personal vehicles, how can we make them more efficient and environmentally sound? What will the automobile of the year 2020 be like?

Cass suggested that a large number of potentially successful technologies—"from a very tight, well-built, durable gasoline-powered vehicle to vehicles powered by alternate fuels to electric vehicles"—could compete to satisfy a requirement that the car of 2020 have virtually zero emissions and degrade gracefully. But we can't wait till 2020. He pointed out that the 20-year-old car of 2020 would be designed in the very near future. "We can't waste any time in requiring that more durable emission-control systems be built into the automobiles that are being designed now." Nichols believed that transition would involve various fuels, such as reformulated gasoline, natural gas, and methanol, but by 2020 "we'll be well on our way to a viable electric car as a result of breakthroughs in battery technology."

Bryson concurred that although "the battery technology is not there today, we see signs that it will move very rapidly." He said that even considering the power plants that would charge those batteries, electric cars would represent about a 97 percent reduction in pollutants over new gasoline-powered vehicles. He and Nichols also agreed that there would be some shift to more mass transportation. The Los Angeles County Transportation Commission is planning $150 billion, Bryson said, in investments in various forms of mass transportation, including electrified buses and commuter rail. These solutions would not, however, deal with the nitrogen oxide problem in the LA basin. "We

Although in the future the Los Angeles basin will see more electric rail, such as the new Blue Line shown here, this will not solve the nitrogen oxide problems.

need to think all these things through in a more integrated fashion," said Bryson.

What all the panelists seemed to agree on was the need for some sort of national energy policy and a government role in R&D, beyond what the market alone can do. Holdren made the point that part of the strategy needed to consist of internalizing more of the environmental costs. "We have to find ways to bring the environmental costs into the balance sheets, into the decision makers' field of vision," he said, "and when we do that, a whole new array of opportunities for cost-effective and efficient energy sources will become attractive. Today at the national level we are spending less than $2 billion a year on all energy-supply R&D," said Holdren. "That's equivalent to a tax of $0.02 a gallon on gasoline in the United States. I'm not suggesting that a tax on gasoline alone is necessarily the right way to raise this money, but the notion that the United States government cannot afford more than $2 billion on all energy R&D is preposterous. The assumption behind it is that the R&D will get done somehow if the government doesn't do it."

So it's a complete nonsequitur to refuse to tax the carbon but then to simultaneously refuse to subsidize the R&D that might make up for the fact that we're subsidizing the carbon.

The others were less circumspect about proposing a tax that would force the producers and users of energy to bear the true cost of the externalities of environmental degradation. "I've never talked to anybody in the oil industry, the utility industry, or at any level of local or state government who believes that the current emphasis on the market as a solution to all of our problems is the right answer for the United States," said Nichols. "Almost everybody who thinks about these issues believes that some form of tax—whether it's a carbon tax or a gasoline tax or whatever is needed—has to be put into research and development." And Noll pointed out, "An absolutely necessary condition to rely upon private R&D to invent new, less polluting energy sources would be that the old energy sources that are polluting would bear their full costs. So it's a complete nonsequitur to refuse to tax the carbon but then to simultaneously refuse to subsidize the R&D that might make up for the fact that we're subsidizing the carbon." Bryson agreed: "I've come increasingly to the view that some form of energy or carbon tax is the right approach to a national energy policy. What we need is an overall tax that gets effectively at the undisputable externalities that are associated with our current energy system."

But R&D won't do it alone. Nichols brought the problem back to land use and the fact that the number of miles people drive has risen twice as fast as the rate of population increase. "Unless we can get a handle on that through attacking the land-use patterns that are forcing people to drive all those extra miles, the technology won't save us." Cass was also skeptical: "New technology is going to be a very necessary and important part of any actual solution to the problem, because the new technology is going to make it that much easier to formulate the solution in a mode that people will accept. But it's not completely clear to me that new technology alone is going to get us where we want to go. We're going to have to have a lot of cooperation from people in their use of that new technology to reduce emissions by 97 percent relative to the completely uncontrolled situation. It takes only a few uncooperative individuals in the population to double the net emissions. I think we are going to have to educate people more clearly about their responsibility to cooperate in this joint venture." □

Water—The Unavoidable Constraint?

"What California has experienced in the last five years could be characterized as a God-made drought, but a man-made shortage."

The session, chaired by Caltech's Norman Brooks, Irvine Professor of Environmental and Civil Engineering, included James Bonner, professor of biology, emeritus; Duane Georgeson, assistant general manager of the Metropolitan Water District of Southern California; James Morgan, Goldberger Professor of Environmental Engineering Science; and Zach Willey, senior economist with the Environmental Defense Fund.

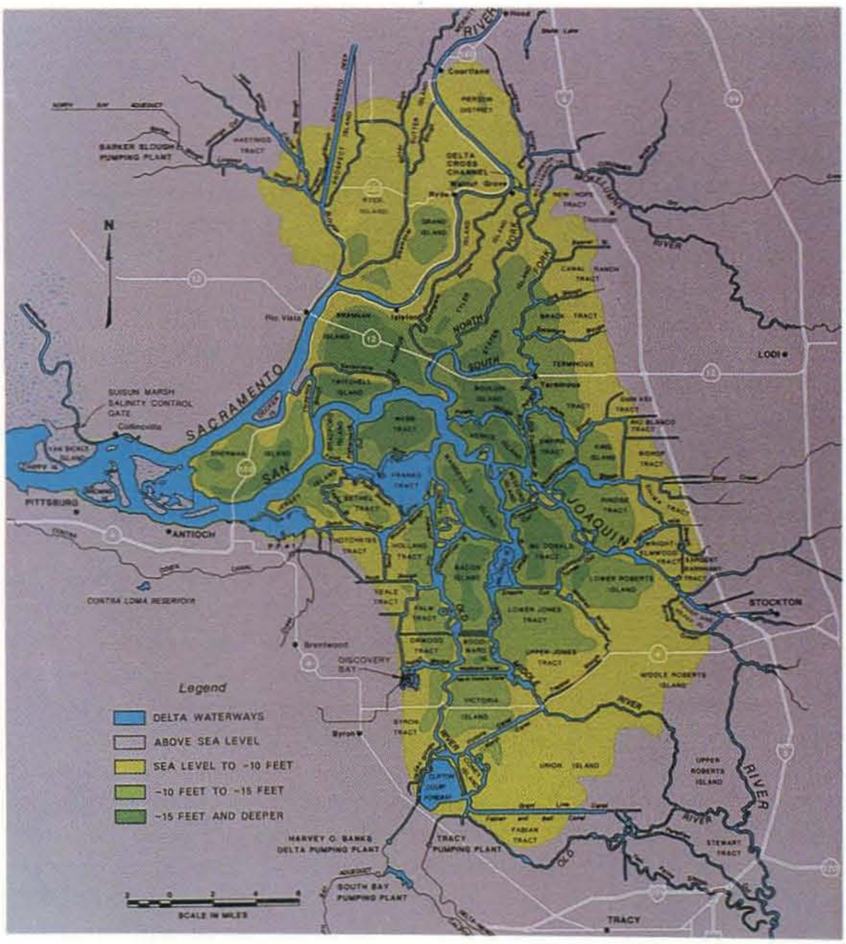
The Edmonston pumping plant on the California Aqueduct near Grapevine lifts water over the Tehachapi Mountains to Los Angeles.

Norman Brooks introduced the session by remarking, "Although most of the water is up north, most of the people are down south. And that only gives you two policy choices—either you move the people to where the water is or you move some water to where the people are."

Zach Willey suggested transferring water from agriculture to the cities and to the environment. "What California has experienced in the last five years could be characterized as a God-made drought, but a man-made shortage." Roughly 70 million acre-feet of water runs off California watersheds each year. (An acre-foot of water—approximately 326,000 gallons—covers an acre of flat land to a depth of one foot, and is sufficient to supply the needs of three average families for a year.) Of that, roughly 40 million acre-feet gets diverted to agriculture and the cities. About 28 million acre-feet irrigates the San Joaquin Valley, and some four million the Imperial Valley and other southern areas. Less than eight million acre-feet goes to the cities. "There's more water used to water feed for livestock than there is to water people in the cities. But there's a complex set of legal, political, and institutional barriers to reallocating water from agriculture.

"Water markets are an economist's dream. As early as the 1950s, economists wrote about the arbitrage potential of shifting water from agriculture uses to city uses." Water from the federal Central Valley Project, which was built for irrigation, costs as little as $10 per acre-foot, yet Los Angeles gets it wholesale from the Metropolitan Water District for $322 per acre-foot. So the incentive for trade exists, but, according to Willey, California's water law is at the tail end of the pack. There's confusion about who owns what, compounded by ambiguous state laws and complicated by third-party claims by environmentalists or other groups whose interests may be affected by the transaction. And should environmental interests compensate other water-rights holders for leaving their water in the river? Wildlife protection is only one environmental use and some of the others, such as white-water rafting and fishing, are big business.

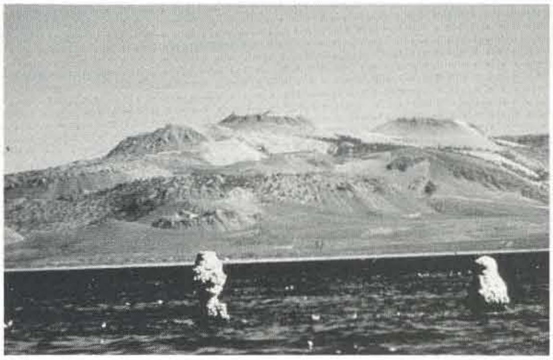
Willey is optimistic that the logjam is going to break. The Omnibus Water Act, signed by President Bush on October 30, 1992, for the first time permits California cities to buy federal water. This water would fetch the sellers—individual farmers and irrigation districts—a price enabling them to finance conservation and more efficient irrigation methods. And the water they save, they can sell—an incentive to finance efficient agriculture. "There aren't a lot of tax breaks to subsidize farmers to increase their efficiency. It's not easy, particularly in Washington, to get subsidies for farmers—there's a feeling that farmers have been subsidized long enough." (The Act has other provisions for California, including setting aside a guaranteed 800,000 acre-feet per year—nearly 20 percent of the project's capacity—to restore habitat damage caused by previous water diversions, establishing a $50-million-per-year fund for environmental repair, paid from water and power sales from the project, and ending automatic renewals of 40-year water contracts to farmers at 1940s prices.)



Willey noted that in Arizona and other states where water transfers occur, some constituencies equate water marketing with promoting growth. "In fact, they're equating water conservation in general with freeing up water for new growth." He sees them as a minority, however, noting that water transfers have many partisans, including environmentalists who want to restore habitats. "Maybe 50 years down the road water marketing won't be taken as an attack on agriculture. In fact, water marketing gives an opportunity for those who can conserve water, or who have marginal land such as irrigated pasture in production, to trade that water and increase the efficiency of their operations. I think there is so much fat in the agricultural-water system that marketing won't touch high-value agriculture."

The Sacramento-San Joaquin Delta, where water is diverted away from the San Francisco Bay and down the aqueducts, is the north-south conflict in a nutshell. Pitched battles over its development have been fought, and will be again. The environmental consequences of diversion are readily apparent: there is less fresh water outflow through the bay to repel the salt water. "Reversals in currents are caused by the way the pumps suck water around the delta islands and back. That's bad for everybody. It's bad for drinking water because it picks up more salt. It's bad for fish because they get confused—the currents are going the wrong way."

Declining populations of several indicator species reflect the delta's health. As water is diverted through the pumping plants, salt water from the ocean intrudes into the bay, and the striped



Opposite page, top: The waterscape of California. Bottom: The Sacramento-San Joaquin Delta.

Above right: Mono Lake in the 1940s (top), 1968 (middle), and 1982 (bottom). Diverting water from the lake's feeder streams to Los Angeles had lowered the lake's water level some 44 feet by 1982. Below: This underground drain was installed near Kesterson to collect runoff water from irrigated agriculture.

bass count declines. "Now with any biological population, you have multivariant causes. Diversion of fresh water from the feeding habitat could be one, but there can be others. Pollution by people in the Bay Area, for example. San Francisco Bay is not by any means a pristine estuary. It is a highly developed estuary and it's been kicked around really hard. Much of it has been filled over the years. The estuary has taken hits, not just from the south but from the north as well." The Dungeness crab, another indicator species, used to have a rich fishery in San Francisco Bay. About the time that fishery vanished, the fishery off Mendocino to the north burgeoned. "So did they die or did they move? I don't know. The point is that environmental arguments are not open-and-shut cases, and that's one reason why the state's bogged down."

But these environmental arguments do affect water rights. In 1989, the National Marine Fisheries Service declared the Sacramento River's winter Chinook salmon run an endangered species, the first migratory-fish run determined to be endangered on the west coast. (Others have since been proposed.) That run "is down to hundreds of individuals now, and there's a debate raging about how to manage Shasta Dam and other facilities to control flows and temperatures in the Sacramento River. And that has implications for the bay and for the water supply for farming and the cities." The Los Angeles Aqueduct, for example, diverts water from the streams leading to Mono Lake, reducing the water level in the lake. In 1983, *Audubon v. Los Angeles*—and subsequent court rulings—restricted the amount of water that the aqueduct could take. The ruling essentially said that Mono Lake is a public-trust resource, and water rights restricting its inflows must be re-evaluated. "The implications for people with established water rights aren't known. And it's that kind of uncertainty that makes it very difficult to engage in orderly water-rights transactions in the way that we would sell real estate, or other assets that have clear legal title."

Once the water has been used, for whatever purpose, some of it—now laden with additional salts and other contaminants—ultimately gets back into the system through drainage channels or outfalls. Irrigating regions that have been dry for millennia can cause other problems, as happened near Kesterson Reservoir, in the western San Joaquin Valley. Marine sediments in the subsurface strata began to leach out through the underground drainage system, and trace elements, including selenium, wound up in the San Joaquin Drain, which formerly terminated in the Kesterson Wildlife Refuge. The water evaporated, concentrating the selenium. "Ironically, Kesterson was originally intended as mitigation for habitat loss in other parts of the Central Valley project, and it wound up having toxic levels of selenium coming from subsurface drains installed to take off drainage water from the irrigated agriculture." In 1982, it was discovered that the nesting waterfowl were laying eggs containing embryos deformed by the selenium. Kesterson was closed, but the drainage problem hasn't been solved. "We've just finished a five-year, $50-million federal task force to try to decide what to do, but as is common in California water right now, there's stagnation."

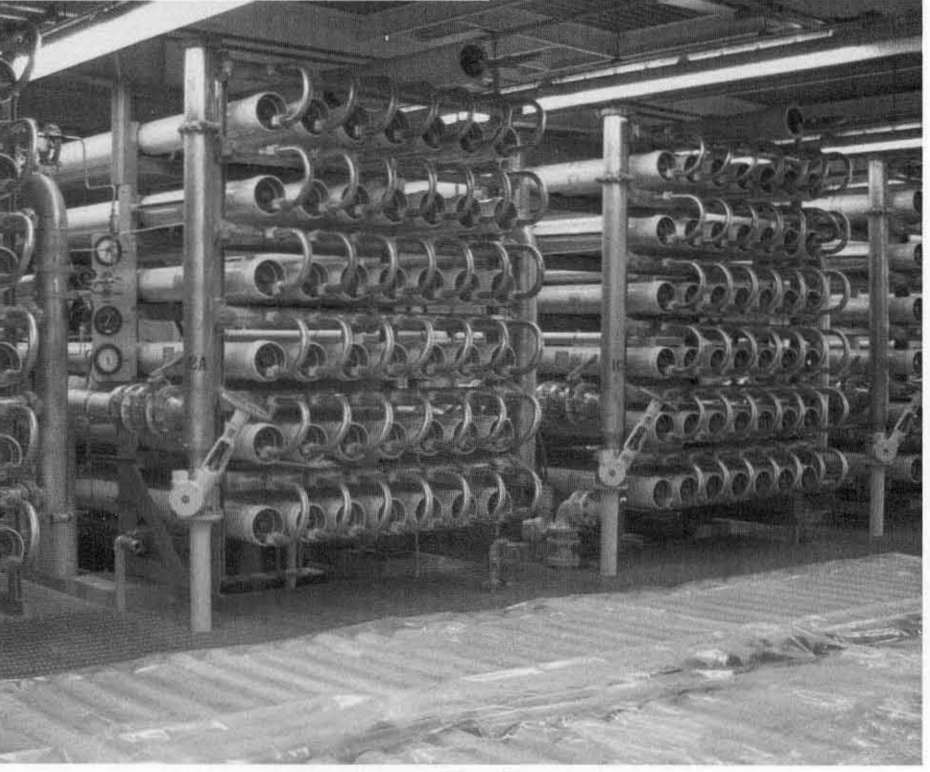
James Morgan pointed out that water quality and water quantity are intertwined. Water analysis is a highly developed science, but "measurements of water quality by professionals and perceptions of water quality by the public are often two different things. It is my perception that the general public is frequently well ahead of the experts in guessing where the next water-quality problems will be."

"We need to worry not only about deterioration under increased use, but our ability to anticipate and cope with unexpected hazards."

Many natural processes and human activities affect water quality. Precipitation washes air-borne pollutants to earth. Runoff and infiltration pick up dissolved minerals from weathered rock and soil, and evaporation concentrates them. "The Colorado River has a total dissolved mineral content of about 600–700 milligrams per liter, or parts per million. If we were carrying those salts to southern California in a railroad train instead of an aqueduct, we would be carrying about 2,000 tons a day, something on the order of 60 railroad cars. In contrast, if we were carrying nitrates, we'd only need a truck. And if we were carrying the dissolved lead, we would need a teacup." Plants draw water out of the soil, leading to salt buildup. And some biological processes are profoundly affected by human activity. For example, eutrophication—the buildup of plant nutrients in standing water—is greatly disturbed by urban and agricultural runoff. Excessive eutrophication causes algae blooms that deplete the water's dissolved oxygen, killing the fish. And domestic wastewater includes other wastes besides the usual sewage. "A number of bad-actor chemicals, inorganic and organic, end up in our wastewaters because of their household uses." And, as San Francisco Bay shows, mixing salt and fresh water changes the salinity, the dissolved organic content, and other parameters of the water, often making it unusable.

On July 14, 1991, a train derailed along the Sacramento River north of Lake Shasta. A tank car spilled 13,000 gallons of the herbicide metam-sodium (sodium methyl dithiocarbamate) into the water, which reacted with it to form the deadlier MITC (methyl isothiocyamate), destroying stream life for 40 miles to the entrance to Lake Shasta. MITC, a volatile compound, also got into the air, affecting the residents of nearby Dunsmuir. "I think that's an illustration of what the future of water quality may be. We need to worry not only about deterioration under increased use, but our ability to anticipate and cope with unexpected hazards. [See "Contemplating the Unexpected" in the Spring 1992 *E&S*.] In a 1987 EPA document called *Unresolved Future Issues,* one of the environmental hazards identified was the possibility that a truck or train would go off the track and spill a large amount of some harmful compound into a freshwater system." At Shasta, fortunately, dilution downstream and natural degradation—primarily by sunlight—prevented significant quantities of MITC from entering the lake, although "EPA scientists reported—off the record—that residual amounts were found in lake sediments. The regulatory irony of the episode is that metam-sodium was not regulated in transportation rules, although the *product* [MITC] is well-known as a hazardous material. The agencies concerned with applications knew that, and indeed, were probably well on the path to regulating the source chemical as well."

Analytical technology and treatment technology evolve in parallel with the technological advances that put increasingly exotic pollutants in our drinking water. In the late 1800s, disease-bearing bacteria and viruses were the main concern. These biological issues were laid to rest with the successive introduction of filtration and chlorination to remove bacteria and to destroy viruses. Now chemical content is the issue. Morgan ticked off a list of pollutants: heavy metals ("There's been considerable discussion about making the lead standard stricter, based on medical evidence, and I predict we'll see greater attention paid to chromium in the next 10 years, as chromium from hazardous-waste sites and household trash landfills finds its way into groundwaters unintentionally as a result of questionable practices."); pesticides and herbicides; solvents including trichloroethylene and benzene, the latter of which "even shows up occasionally in water imported from France"; and various other organic chemicals such as PCBs (polychlorinated biphenyls). Recently, byproducts of disinfection became an issue, when it was discovered that chlorine reacts with the decay products of agricultural and natural runoff to form chloroform and other trihalomethanes. And radioactives such as alpha emitters and radon-222 are a concern. Basic physical issues, including the



"The balance swings between birds and people—the trick is to keep your eye on both concerns at the same time."

This reverse-osmosis unit can remove the dissolved salts from 5 million gallons of treated municipal wastewater per day. It is part of a multiple-stage system at the Orange County Water District's Water Factory 21, an advanced water-reclamation plant. The water is purified to drinking-water standards, then injected into the Orange County groundwater basin through a series of wells. The process replenishes the groundwater basin, from which 70 percent of the county's water is drawn, and prevents seawater from flowing into the basin and contaminating it.

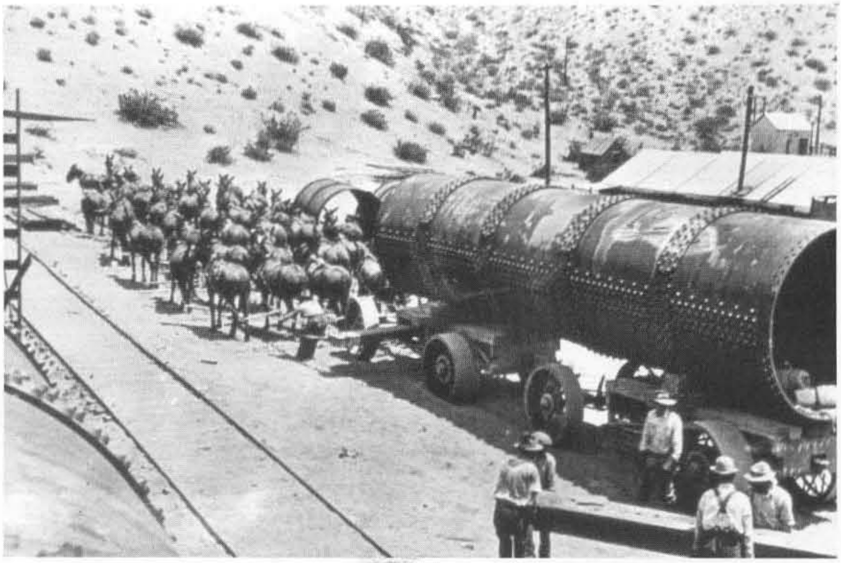
clarity of the water, as well as its color, temperature, taste, and odor, also remain—what water purveyors call aesthetic considerations. These aren't inimical to health, but make the water supply appealing and determine whether it's used.

"It might be instructive to take a historical glance at drinking-water quality standards. In 1925 eight inorganic chemicals had standards set, plus bacteria, clarity, and odor. In 1942, the list included 12 inorganic chemicals, one organic chemical—chloroform—and the bacteria and the aesthetic considerations. By 1962, the requirements comprised 17 inorganic chemicals, three organic chemicals, and, for the first time, three radioactives. In 1990, the standards totaled 22 inorganic chemicals, 43 organic chemicals, eight radioactives, and now foaming agents. It's likely that by the end of this century, there will be well over 100. You can trace the history of modern times in the water standards. Every water utility, public or private, must publish an annual report on the quality of the water distributed to the consumer. We're a highly regulated society with respect to water quality. Our tap water is safe. It's a different matter, of course, whether the water is aesthetically pleasing, and that may be one reason why some people prefer bottled water.

"It's my opinion that much less attention has been given to the scientific basis for the water quality needed to protect ecosystems than has been given to the scientific basis for protecting human health. Ecosystem water-quality science is still in a catch-up mode. That's part of the difficulty in understanding the quality issues in the bay-delta system." Ecosystem health can be affected by disturbances of natural flows of carbon, phosphorus, nitrogen, and acidity; sediment loads that influence light; and man-made chemicals such as PCBs and the even more toxic things that these may transform into. "Twenty years ago, human toxicology and ecotoxicology were more in balance. But ecotoxicological criteria were perhaps oversold in the 1972 Clean Water Act, and there's been a subsequent backlash in that ecologically based standards didn't always give clear-cut results. The balance swings between birds and people—the trick is to keep your eye on both concerns at the same time.

"The traditional approach of developing and protecting high-quality water sources will not be sufficient. The challenge will be the management of complex issues. Models that relate water quality to water quantity and chemistry to biology will play a larger part in decision making in the next century. Maintaining water quality is going to require more accurate measuring of a variety of things. Many people have said that this is going to be the information society, and this will be especially true of environmental decision making.

"California's surface reservoirs hold perhaps 45 million acre-feet, whereas the groundwater reservoirs, developed and undeveloped, hold something close to 800 million acre-feet. I think they'll increasingly be used to store water, avoiding evaporation loss. Where the character of a particular contamination is well-defined, there will be a very strong impulse to perfect the technology required to treat it." (Duane Georgeson pointed out that desalting, via reverse osmosis



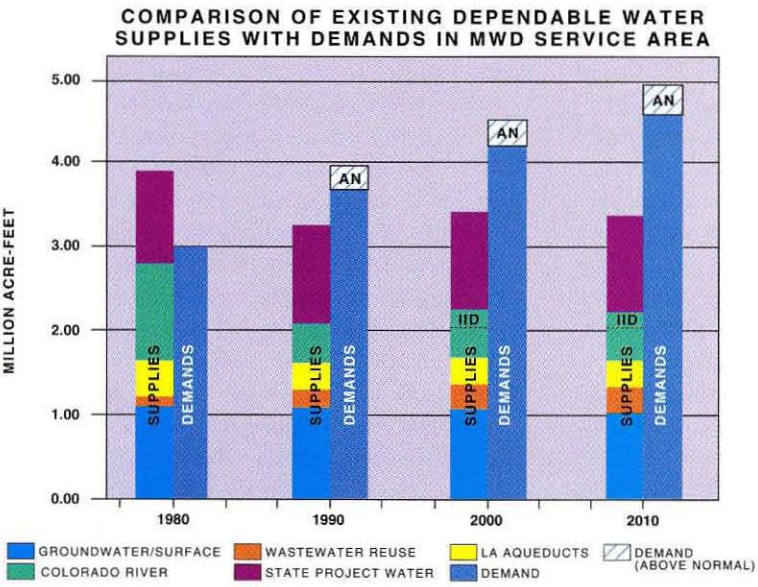
Above: The Los Angeles Aqueduct under construction. Below: Workmen building the Colorado River Aqueduct's San Jacinto Tunnel. The tunnel, which pierces the San Jacinto Mountains, is some seven miles long.

and electrodialysis, is already prevalent in groundwater basins that are brackish or have high nitrate levels. Desalting for drinking water, as on Catalina Island, is much rarer.) Morgan predicted that the already extensive reclamation and reuse of waste water will expand as the water-quality criteria for different uses become sharpened, and the risks of agricultural, recreational, and drinking-water uses become scientifically understood and technologically controllable.

Georgeson used the Metropolitan Water District of Southern California (MWD) as an exemplar of how growing demand can be met with shrinking resources. He started with a history and geography lesson. MWD was created by the state legislature in 1928, originally to finance, construct, and operate the Colorado River Aqueduct. It's composed of 27 member agencies: 14 cities such as Los Angeles, Santa Monica, and Pasadena—the smallest being the city of San Fernando—and 13 districts, starting in Ventura County and stretching south to the San Diego County Water Authority. It supplies supplemental water to about 95 percent of the people living in the coastal plain.

Several aqueducts supply water to southern California. The initial one, the Los Angeles Aqueduct, completed in 1913, "was the first great experiment in water marketing in California. Zach would probably say it went a little too far, in terms of setting a good precedent. In 1906, President Theodore Roosevelt made the judgment, based on the greatest good for the greatest number, that the water from the eastern Sierra would be better used by being exported to Los Angeles." Number two is the Colorado River Aqueduct, conceived when Hoover Dam was being planned. The aqueduct starts farther downriver, where Parker Dam created Lake Havasu. A series of canals, pipelines, and six pumping plants brings the water to Lake Mathews, south of Riverside. "In an era when the financing of water projects is controversial, particularly during a recession, it's interesting to note that this project was approved by the voters of southern California in 1930, just as the Great Depression was beginning, and that it was built to provide a future supply to this area." The third, the State Water Project, approved by a razor-thin majority in a statewide vote in 1960, begins with Oroville Dam and reservoir on the Feather River at the north end of the Sacramento Valley, and eventually the California Aqueduct brings the water to Pyramid and Castaic Lakes in the mountains north of L.A. "The costs of these projects tend to go up by a factor of 10. The Los Angeles Aqueduct was built at a cost of $22 million, which was a huge sum of money in 1913. The Colorado River aqueduct was built at a cost of $220 million during the Depression, and the State Water Project, in the 1960s, cost approximately two billion dollars."

Southern California gets about two-thirds of its water from pipelines and the rest from local groundwater basins, which helps regulate the consumption of imported water. "Currently, the total water use in our service area is a little under four million acre-feet a year, or about four billion gallons a day. The existing aqueduct systems, together with the local groundwater basins, are capable of supplying about five million acre-feet. So where's the problem? The problem is that those imported sources, and even our local supplies, are no longer reliable." The Los Angeles Aqueduct delivered nearly 0.5 million acre-feet per year for the last 20 years. Currently, because of environmental issues—Mono Lake litigation and Owens Valley groundwater problems—it supplies less than 200,000. The Colorado River Aqueduct has been running at 1.2 million acre-feet for 25 or 30 years, but about half of that supply will soon go to Arizona, as that growing state



Southern California's dwindling dependable water supply, plotted next to southern California's burgeoning water demand, assuming that water-conservation measures are not invoked. The "above-normal demand" represents a worst-case projection. The piece of the green bar above the dotted line labeled IID is the water MWD plans to acquire by paying to line the All-American Canal.

"The courts are sometimes seen as a way to find resolution, although you have to make sure you start with young attorneys because the litigation frequently lasts a long time."

exercises its water rights. Southern California has rights to two million acre-feet from the State Water Project, which in 1991 barely met 15 percent of its obligations, due to the drought. "During the 1980s, southern California's reliable supply dropped to about 3.3 million acre-feet, while our use grew from about three million acre-feet to four million. The two lines crossed."

And the local supply is subject to groundwater contamination. Many coastal, and some inland, areas have high mineral content from seawater intrusion or agricultural drainage. There's nitrate buildup around the dairies in the Chino basin and in other agricultural areas. And there's extensive solvent contamination in many places, including the San Fernando and San Gabriel valleys, and around Burbank Airport.

Georgeson outlined MWD's strategy to restore reliability through demand management, wastewater reclamation, water transfers—primarily from agriculture—and infrastructure improvements. "We've just reached a milestone agreement after two years of hard work with six urban water agencies in the Bay Area, including the city of San Francisco, and half-a-dozen water agencies from southern California, along with groups like the League of Women Voters, the Sierra Club, and the Environmental Defense Fund. In some respects, it's not that the water agencies are able to work with the environmental groups that's surprising, but that the agencies in the Bay Area and southern California are working together." The agreement includes promoting water conservation at the consumer level—such things as giving away low-flow shower heads, rebates on water-saving washing machines, and consulting with industrial customers on improving the efficiency of their water use—a radical departure from the old mindset of selling all the water the customer could swallow. And MWD encourages its subagencies to do likewise. "We pay up to $154 per acre-foot to subsidize wastewater reclamation projects. Reclaimed water can irrigate golf courses, cemeteries, parks, playgrounds, and freeways, and can recharge groundwater basins. We have a similar subsidy on water conservation, for things like retrofitting ultra-low-flush toilets. California as a state may be lagging, but southern California is making significant strides in water transfers. We will pay the Imperial Irrigation District about $128 million to line some of their canals, and in return we'll get the 106,000 acre-feet of water per year this will conserve. We have a similar program to pay the federal government around $100 million to line the All-American canal and save perhaps another 75,000–100,000 acre-feet. We have another innovative program whereby we'll be storing water in the Arvin–Edison District south of Bakersfield. In wet years, we'll store water in their groundwater basins, and in dry years they'll pump it out with facilities we will build for them. In return, we'll get some of their surface water. Our efforts should net us almost 400,000 acre-feet per year by 1994, growing to about 700,000 acre-feet per year by 2010. That's more than the total water use in the city of Los Angeles. But there are a lot of uncertainties, because these projects usually involve negotiations with many other players to solve institutional, legal, financial, and water-quality problems.

"We've been on hold for 15 or 20 years while the different interests—agriculture, the cities, and the environmentalists—all saw water management in terms of meeting their own needs, with no one group strong enough politically to have its way. As a result, there's been a deterioration in the reliability of southern California's water supply, with water rationing this year for the first time, really, in history. And agricultural areas throughout California are living on short rations, and mining their groundwater basins."

Georgeson sees conflict resolution through negotiation as the way of the future, along with making better use of our resources, especially the groundwater basins. "The courts are sometimes seen as a way to find resolution, although you have to make sure you start with young attorneys because the litigation frequently lasts a long time. The city of Los Angeles just signed an agreement with Inyo County on restricting groundwater pumping in the Owens Valley, "We live in a postindustrial society. But there has never been a postagricultural society. Everybody still eats."

ending a lawsuit filed 19 years ago. And Colorado River litigation, needless to say, is job security for a lot of attorneys up and down the river."

Similar negotiations between the agricultural water agencies, the urban water agencies, and about a dozen environmental groups are trying to resolve the delta's problems. "A key part of resolving the issue of how to build and operate facilities in the delta is to provide some kind of permanent guarantee that could not be upset by political processes, or even by a vote. And so a lot of attention is being given to institutional mechanisms—perhaps some kind of contract that would lock in guarantees protecting the fisheries and other environmental values. The delta is an area of great conflict, but if it's going to continue as the source of drinking water for the 20 million Californians in the north and south who depend on it today, we're going to need better facilities."

MWD's major new construction project is in line with their get-more-from-less approach—an off-stream reservoir in Riverside County near Hemet to store water in wet periods for use in dry ones, and to recharge local groundwater basins. It will store water that becomes available from the Colorado River or the state water project in wet winters. "We don't have room in our spreading grounds. Typically, if it's raining in northern California in the winter, it's raining in southern California. So we'd fill this new reservoir in the wintertime and then transfer that water to groundwater basins in the spring, summer, and fall."

The Colorado River Aqueduct crosses an awful lot of desert to bring water to the cities of southern California.

Regional and state planning agencies have recently raised the population projections upon which MWD bases its plans. "So now, even with these programs, there would be many dry years when we will continue to be in the market to buy large quantities of water from agriculture."

James Bonner went to bat for agriculture. "We live in a postindustrial society. But there has never been a postagricultural society. Everybody still eats. The recent history of California agriculture is Orange County, which used to be a monolayer of orange trees as far as the eye can see. We've cured it of that. And before that, Los Angeles County was the biggest single agricultural produce-producing county in the United States. We sure cured L.A. County of that, too. Agriculture was the biggest producer of export revenue for California—about an \$18-billion-per-year business—before we embarked on making defense equipment. Today, we have left the great Central Valley and the Imperial and Coachella valleys further south, in the region of the Salton Sea. These are incredibly productive agricultural areas—high-technology, sustainable, irrigated agriculture that doesn't salinize the soil. Zach said that we use this water to grow low-value feed for animals. Most of that is alfalfa. Alfalfa produces more protein per acre than any plant or animal we know of. It's a complete diet—human beings could live on alfalfa if they just would. All the amino acids, the vitamins, everything you need is in alfalfa. That's why it's grown to feed animals. We also produce high-value crops such as a specialized variety of cotton, sold with guaranteed physical specifications—fiber length, fiber strength, and so forth. It's what Levi's jeans are made of, and is sold in vast amounts to Japan to make high-fashion clothes. We grow fruits, raisins, fresh grapes—all kinds of goodies—and the Imperial and Coachella valleys produce all sorts of nice vegetables for the winter season.

"Now it's true that these crops use water. So I had thought that our last protection against infinite population growth would be that we'd share the water between agriculture and the cities, and the amount left over from agriculture would determine how many people we could accommodate. But it looks like people are getting priority, and that's what I'd like to head off if we can. Farmers *do* get water cheaply. We can increase the price. I would argue as the Japanese government does: they're very particular about maintaining their ability to grow rice, so that if they ever need to, they can still grow their own. Let's keep our little bit of agricultural productivity alive so that when the time comes, we can grow our fruits and vegetables ourselves."

Georgeson noted, "As a matter of fact, intensive agriculture in the San Joaquin Valley uses 2.5–3.5 acre-feet per acre, and water use in a typical urban area in California is about the same. So you could convert all of the agri-use in the San Joaquin Valley, and get enough water for 100 million people, God forbid. My own view is that controlling population or managing growth is an exceedingly difficult subject that's tied up with national immigration policy, the economy, etc."

Willey had the last word. "I think we can balance all these competing uses and still have plenty of water for growth. We don't always use the same amount of water per unit of gross-national-product growth. Technology changes. Incentives change. We can accommodate a different type of growth using a lot less water and a lot less natural resources. That makes me feel fairly bullish that in the next 50 years, we can restore much of the environmental damage, take care of a lot of people, and still have agriculture. I think we're very lucky. We've got lots of options, and water, I think, is not the issue in California. Other constraints are the issue." □

Realities for a Sustainable California

Just as we need to have concerted action to compel attention to managing our natural resources, we need to insist on attention to our human resources.

by Shirley M. Hufstedler

I think it is fair to say that the visions of the California panel have been neither beatific nor apocalyptic. Rather, one gets the distinct impression that the speakers, in an optimistic frame of mind, decided that the problems have been solved. Few of the speakers have leaped forward to offer their visions, either frightening or intoxicating, of a hundred years hence. I find this rather surprising, because I think it is a wonderful exercise; unlike talking about things in a nearer time frame, you know full well that neither you, the speaker, nor your audience will be around to find out if you are right.

I think we may be rather timid about our assumptions of what is going to happen in a hundred years. We should not make the mistake of believing that technological change and innovation are going to proceed only linearly or perhaps arithmetically; change could proceed exponentially and create opportunities which we can be only dimly aware of at this time. Who knows? It's even possible that we might make a breakthrough in what really needs doing—changing the habits of mind that have afflicted and only occasionally inspired human beings. These are the most difficult things to change. Most of the speakers at this symposium have talked about the natural environment—its distortion, destruction, or enhancement. But the life processes that we depend on, the processes of *human* creation and survival, so awe us that we tend to reject thinking about them at all.

Can you envision a period a hundred years from now in which the war between the sexes would finally end in a treaty that was fair? Can you imagine a time when men would not consider it necessary to launch a big power trip over women; when women and girls would be valued individually, not simply for their recreational or procreational capacities; when women would not end up having to do all of the work, paid or unpaid, that men have never wanted to do; when women are treated as human beings with the kind of aspirations and opportunities that men have always enjoyed? Then we would move into a true partnership. Among the many things that might result is a significant reduction in the level of violence in all societies. I think it would also mean that the children of the future would have a better opportunity for rewards in their own lives and for contributions to their societies.

But if we try to predict such rosy qualities merely 50 years from now, we run into trouble, because we know some things about who will be here at that time and what they will be like. Millions of Californians who will be here then are here now. They are being born every day; they are in playpens and in preschools, and some of them are in elementary schools.

What do we know about these children? Today, more than 15,000 babies are born every day in California. Of those, more than 20 percent are born into poverty—into conditions that we like to think are associated only with the sadder developing countries. And the proportion of California children living in deep poverty is growing extemely rapidly. In the past decade the number of very poor children increased by 50 percent in 40 counties and doubled in 17 other

Now, what kind of California are we going to have 50 years from now with a population that has been reared under such conditions?

counties. As many as 20 of California's 58 counties have rates of low birth weight that are worse than those in Egypt. More than half of all children are not vaccinated against the most common infectious diseases. Thousands of California children are homeless. In many of California's school districts, 40 percent of the youngsters drop out of high school. Quality day care for young children in every economic stratum is inadequate, and for the children of the poor, the situation is desperate.

Now, what kind of California are we going to have 50 years from now with a population that has been reared under such conditions? If a natural disaster or a foreign enemy were destroying hundreds of thousands of the children of this state, there would be an immediate outcry. We would demand that governments take action. We would expect an outpouring of voluntary contributions. But that isn't happening. Why not? Children of the poor are invisible to the affluent. Those children don't play in *my* playground. They don't even walk in my street. The care of young children does not provide desirable jobs for men; child care has traditionally been an occupation of unpaid women or very poorly paid women. It still is. Taxpayers' rebellions that so successfully swept California and moved across the United States and settled into Washington, D.C., have dismantled the basic infrastructure available to children, particularly to poor children. Medical clinics serving these youngsters, Head Start, nutritional programs, family-planning programs, have all been cut to pieces. It doesn't take a vast fortune to take care of those kids. We could meet the basic needs of these youngsters for about $20 per taxpayer per year.

The failure to coordinate the services designed to serve children is pervasive in this state and across the United States. This is yet another aspect, and, I think, the most important one, of a problem that has been discussed throughout the California sessions of this symposium—the lack of coordination between the various arms, legs, and toes of government. But we can fix it if we have the political will to fix it. The only thing standing in the way of changing the future of this state and of the United States is building the political will to do it—to insist that the agencies that are supposed to provide social services to children and others be run for the benefit of those who are supposed to be served, rather than for preserving the turfs and the jobs of those who happen to inhabit them as bureaucrats or political figures. Everybody can do something. Just as we need to have concerted action to compel attention to managing our natural resources, we need to insist on attention to our human resources. We've got to clean up our act as well as our air and water if we are to have a future state of California in which we ourselves would be willing to live.

Shirley Hufstedler, Secretary of Education during the Carter administration and a former judge of the U.S. Court of Appeals, now practices law in Los Angeles. She is a member of Caltech's Board of Trustees. Hufstedler graduated from the University of New Mexico in 1945 and earned her law degree from Stanford in 1949.

Judge Hufstedler's talk opened the final panel discussion, which she moderated. Also participating were Bruce Cain, Glen Cass, Duane Georgeson, Mary Nichols, and Roger Noll.

California's problem is the national problem of shortsightedness.

Shirley Hufstedler's emphasis on *human* resources as key to California's future was echoed by the rest of the panel, which was charged with the task of wrapping up the day with a discussion of "Realities for a Sustainable California." Duane Georgeson and Mary Nichols both stressed the importance of education and diversity. Georgeson mentioned that, particularly with urban problems in a rapidly changing area like southern California, "we have to take advantage of all the talent that's available—all the ethnic groups and certainly women." He noted that in engineering the dramatic change in participation by women and different ethnic groups has "brought a lot of rich new ideas in terms of how we approach the solutions to problems of dealing with urban infrastructure."

"I'm bullish about technological fixes that can help us get out of our problems of air pollution, water quality, and transport," said Nichols, "but the software that goes with all of that hardware is going to require people who not only have a high degree of educational ability, but also who know how to work with people of different racial, ethnic, and economic backgrounds."

Glen Cass was also optimistic about technology's potential to help solve California's problems, and he saw as the symposium's unifying theme the attempt to answer the question, "Which resources are truly limiting in terms of sustaining pleasant life?" He asserted that the availability of fossil fuels and water were not limiting constraints, nor was technological innovation. "The true limiting resource is clearly people," said Cass. "And I don't mean limiting in the sense of quantity. I mean limiting in the sense of the need to increase the coincidence of values shared by the people in our society." He noted a willingness to cooperate and an improved educational system as necessary conditions for continued technological innovation. "And finally, we're going to have to provide environmental progress rapidly enough to prevent the flight of human capital from southern California, so that the people who have the skills to solve the problems still live here long enough to, in fact, solve them."

Hufstedler's remarks on the problems of education and children in poverty were picked up by Roger Noll, who claimed that a reduction in the size and scope of government expenditures did not occur in the eighties, but that there was "a shift in what was regarded as important. What happened was that the amount of money spent on older people went up dramatically, contrasted with the amount spent on younger people."

"Declining poverty among the elderly is one of the success stories in the United States in the past 25 years," continued Noll. When poverty became a dominant issue in about 1960, most poor people were old and most of the old were poor. This is now far from the case, and the biggest change has come in medical care, which represents 12 percent of GNP. "About half of the money we spend on medical care is for people in the last six months of their lives," said Noll. "When we started Medicare, the fraction of GNP spent on medical care was about 4 percent. So therein lies the problem with regard to the budget, with regard to the children, and with regard to long-term planning for the future of all forms, including energy and environmental policy." Noll hastened to add that he was not blaming the elderly. Nevertheless, their economic improvements have come at the expense of other federal programs and especially children. The challenge is to restore balance to national policy between consumption, especially for the elderly, and investment. On these issues, "California's problem is the national problem of shortsightedness."

Bruce Cain continued this theme: "The problem is not the number of people, or the capability of people, but the shortsightedness of people: the shortsightedness with respect to time—not seeing that what you do at this moment may have implications down the road; shortsightedness with respect to place—not realizing that the water you're draining in Mono Lake for southern California might affect the quality of life of people in the Sierra, or that the

Smog blows through Cajon Pass in 1975. Emission controls on automobiles since then have been responsible for dramatic improvement.

What people are optimistic about today are the opportunities *for sustainable life-styles and improvement in California.*

housing project you build in Pomona might have implications for commuting in Pasadena." Cain also mentioned shortsightedness within groups—"the idea that we take care of ourselves in the middle class and we don't need to worry about what's going on in the poverty areas of the state or what happens to children in the ghetto in terms of the waste of human potential."

Part of this shortsightedness is due to the divisions within the state, said Cain—divisions between north and south, rural areas and urban areas, whites and nonwhites. "It's particularly difficult in a fractured and decentralized political system to get people to see beyond the parochial parts of their world," Cain continued. "It's hard for people to see the connections and the interdependence when they don't correspond to existing levels of government or representation." Cain returned to the point he had made in his talk about the need for a regional level of government to deal with regional problems. But it's hard for cities and counties to develop regional strategy without leadership at the state and national level, he said. "The lack of consensus in society is manifested in divided control at a lot of different levels with different levels of responsiveness to the public." This is going to make innovation and radical change difficult, Cain said.

All the panelists seemed optimistic about California's long-term future, although there seemed to be a number of doubters among the questioners in the audience. Summing up the general attitude of the speakers, Noll claimed that "California is, in great measure, in control of its own destiny within the time horizon that we are contemplating at this conference." Cain held back a bit and maintained that, although he didn't envision any cataclysmic scenario, such as mass starvation or a state in ruins, there are "intermediate steps of hell and heaven here." He thought that "it's quite possible that in the next 10 or 20 years there may be some deterioration on the margin in the quality of life, and we'll have to cope with that." Georgeson believed that "we should not too quickly despair of the ability of human beings to respond to challenges. I think that, as things change, they evolve, and human beings, with their various institutions, devise solutions to problems."

Nichols, too, was hopeful because of California's leadership in change. She mentioned California's leadership in higher education and was even optimistic about some of the state's bad features. "It gives me some hope," she said, "that southern California, probably the worst example in the world of a wasteful, sprawling urban area, has already made changes that decouple our industrial and residential growth from increasing use of energy. If we can continue to make progress in our *worst* area, the transportation sector, I think we can have a claim to something that we can export to the rest of the world." Cass thought that the optimism of the California sessions, as opposed to the pessimism of the symposium's sessions on world sustainability, centered "around the concept of opportunity. What people are optimistic about today are the *opportunities* for sustainable lifestyles and improvement in California." Noll, however, had commented earlier that "the fact that the opportuni-

I think that in 50 years our grandchildren will find it preposterous that the world, and particularly the U.S., should have been so wasteful of irreplaceable natural resources.

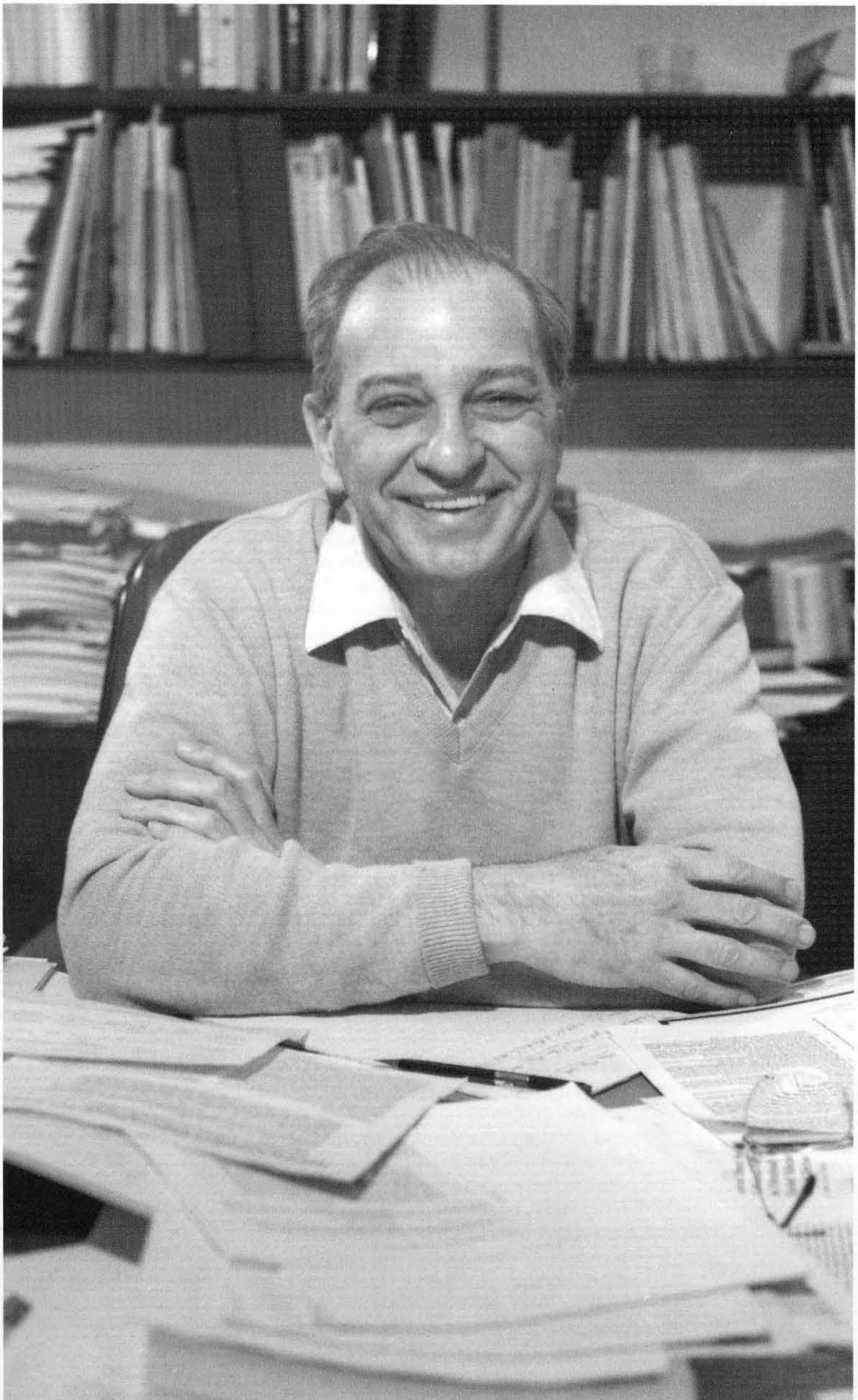
ties exist does not mean that we will, in fact, take advantage of them."

Noll pointed out that in dealing with California, "we are talking about a very tiny fraction of the world's total population. The fact is that there are 30 million of us and 5.3 billion of them." But if we take into account the extent to which the world's problems impinge on California, we can approach it in two ways. The first is the self-interest argument, which economists deal with in general equilibrium models—for example, global climate models. "If the rest of the world does itself in, it will drag California along with it." But, using the self-interest argument, population growth in Africa or Southeast Asia is not perceived by most of us to have much of an effect on our personal income or lifestyle.

"Then, there's the second argument—the altruistic argument," Noll went on. "And that's the ethically persuasive one to me. Even if my own welfare in my lifetime and my daughter's welfare in her lifetime and everyone's welfare in California is not much affected by, say, species extinction in the Amazon Valley, nonetheless, I still hold it to be of value and I'd be willing to do something about it. But the difficulty lies in the fact that we're not living in an age with a long, altruistic time horizon. How are we going to convince people to respond to that kind of an argument?"

Shirley Hufstedler, as moderator of the last panel, continued the theme in her summary of California in the world community. Having been instructed to sum up not only the day's sessions on California, but the entire symposium, "in a manner that is cogent, touching, witty, and encompassing—in four minutes," she made a valiant attempt: "I think we can say that a consensus has been reached on a few points. One is that whatever reasons may have motivated governments in an earlier day to keep prices for petroleum products unnaturally low, it is a policy that must go. Second, conservation and greater efficiency in the use of critical resources in the short term can help us bridge over to the point where technological advances will be able to stretch out the benefits of those resources. I think that in 50 years our grandchildren will find it preposterous that the world, and particularly the U.S., should have been so wasteful of irreplaceable natural resources. In various ways each one of the panelists has noted that many people who have the luxury of any choice at all will make a choice that is more beneficial to the globe and to the salvation of irreplaceable resources if the sacrifice that they are required to make is not so severe as to be unbearable.

Third, and extremely important to the United States, the allocation of the burden must be fair. It doesn't have to be perfect. It doesn't have to be exquisitely equitable. But it should not be grossly unfair, either in fact or in perception. And finally, I think that everybody on the panel has agreed that we have to develop some kind of policy to protect the commons. The commons may be variously defined—many things such as water or information that have traditionally been considered private property are now being redefined as part of the commons—but we must begin to develop a series of incentives and disincentives that push people into doing the right thing, at least until we can do better in the modification of human behavior. We also need to get together and talk to one another about these issues—and talk to legislators and to candidates for office. We should ask them what they intend to do about these issues, and not settle for the response that they're going to run on behalf of anyone who is willing to give them enough money for their television spot. We can do better than that, ladies and gentlemen. We all can." □



Rudy Marcus Does Dynamite Work

The problem... was to explain why, when you have a bunch of ions in solution, electrons sometimes leap from ion to ion with dazzling speed, but other times don't seem all that interested in venturing forth.

by Douglas L. Smith

Caltech's newest Nobelist, Noyes Professor of Chemistry Rudy Marcus.

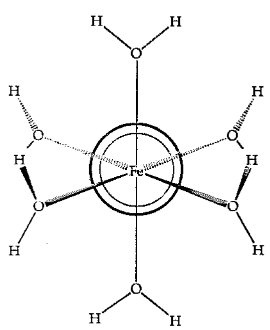
On Wednesday, October 14, 1992, Rudolph A. Marcus, the Arthur Amos Noyes Professor of Chemistry, became the 21st Caltech alumnus or faculty member to win the Nobel Prize. Marcus is the second faculty member to receive the prize for chemistry—the first being Linus Pauling in 1954—and the most recent winner since William A. Fowler, Institute Professor of Physics, Emeritus, got his for physics in 1983.

The Nobel citation read in part, "Marcus is being rewarded for his theoretical work on electron transfer—work which has greatly stimulated experimental developments in chemistry. The processes Marcus has studied... underlie a number of exceptionally important chemical phenomena, and the practical consequences of his theory extend over all areas of chemistry. The Marcus theory describes, and makes predictions concerning, such widely different phenomena as the fixation of light energy by green plants, photochemical production of fuel, chemiluminescence ("cold light"), the conductivity of electrically conducting polymers, corrosion, the methodology of electrochemical synthesis and analysis, and more.... In the mathematical connection the Marcus theory makes between theoretical and experimental quantities, experimental chemists gained a valuable tool."

When Marcus did the work that would win him the prize 30 years later, he was an associate professor just starting his academic career at Brooklyn Polytechnic Institute. (He came to Caltech as the Noyes Professor in 1978.) The problem Marcus originally tackled was to explain why, when you have a bunch of ions in solution, electrons sometimes leap from ion to ion with dazzling speed, but other times don't seem all that interested in venturing forth. Iron, for example, has two common ionic forms: an electrically neutral iron atom (one with all its electrons) can give up two electrons to form the "ferrous" ion (Fe^{+2}), or it can lose a third electron and become the "ferric" ion (Fe^{+3}). If you have a mixture of Fe^{+2} and Fe^{+3} ions dissolved in water, it should be no great feat for that third electron on an Fe^{+2} ion to trade places by jumping to a nearby Fe^{+3}—which then becomes an Fe^{+2} ion—while the spurned Fe^{+2} ion becomes an Fe^{+3}. (The electron loss by the Fe^{+2} ion is called "oxidation," and the electron gain by the Fe^{+3} ion is called "reduction.") After all, no bonds are being broken or formed, and no atoms are being rearranged, so there should be no impediment to swapping electrons. And electrons are notoriously flighty, will-o'-the-wisp particles. Yet experiments to measure this so-called self-exchange rate have found that, at the acidity and ionic concentrations normally used, it takes several minutes for half of the ions to trade electrons. But if each iron ion is surrounded by a sextet of cyanide ions in what's called a complex ion, the same self-exchange reaction happens about 1,000 times faster.

(Chemists measure these reaction rates by "labeling" one of the participants isotopically. Isotopes are atoms of the same element that differ in the number of neutrons in the nucleus. An isotope with an extra neutron or two is marginally heavier than, but chemically identical to, its lighter brother. For example, the chemist could start with all of the original Fe^{+2} ions being of ordinary iron, and a trace quantity of the Fe^{+3} ions being of iron-57—an isotope containing one extra neutron. At a fixed time later, the chemist separates the two isotopes and determines how many of the iron-57 atoms are now in the +2 state.)

So what determines how fast a reaction goes? In 1952, Willard F. Libby, then at the University of Chicago, realized that the solvent molecules immediately surrounding the ion held the key. Most solvent molecules, although uncharged as a whole, have a very specific internal charge distribution that causes the molecule to behave as a dipole. In a water molecule, for example, the oxygen atom attracts electrons more strongly than the hydrogen atoms do, so the oxygen end of the molecule winds up with a slight negative charge, and the hydrogen end with a corresponding positive charge. Though less than the charge of one electron, these partial charges are noticeable to the outside world. As a consequence, an ion in solution isn't merely awash in a sea of free-floating solvent molecules. It creates its own following in the half-dozen or so solvent molecules immediately surrounding it. Drawn by the ion's charge, this shell of molecules attempts to dance attendance on the ion like a group of sycophantic courtiers around a king. Each solvent molecule puts its best foot forward, presenting the portion of its anatomy that is most attractive—i.e., most oppositely charged—toward the ion. The molecules take up very specific posts around the ion. The exact position of each molecule relative to the ion, as well as the number of molecules allowed into the charmed circle, is determined by the specific ion being surrounded. Solvent molecules farther away feel the ion's presence also, but, as in any autocracy, their slavishness decreases as their distance from the center of power increases.



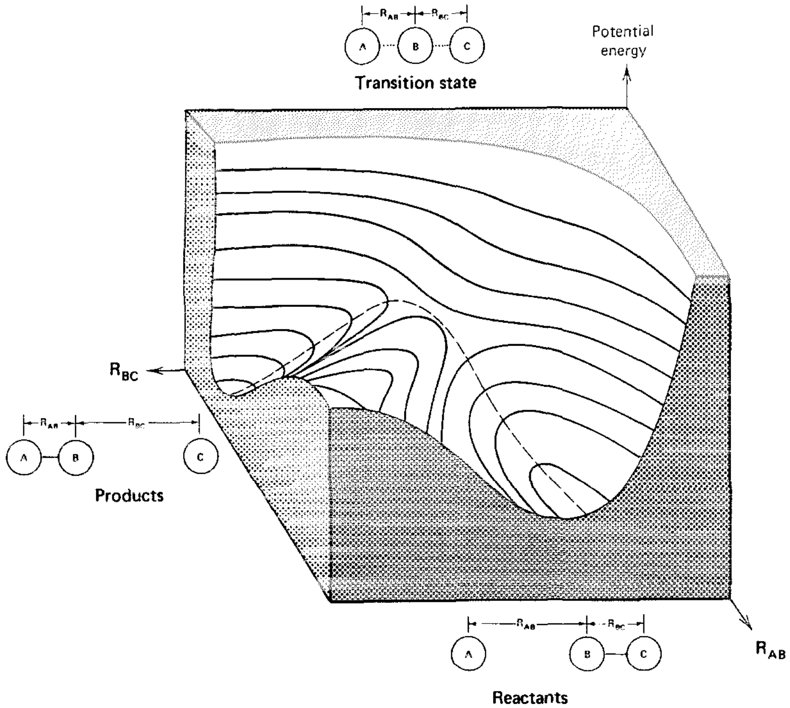
An iron ion surrounded by its six closest water molecules. The heavy outer circle represents the Fe^{+2} ion; the lighter inner circle is the Fe^{+3} ion. Solid arrows indicate bonds sticking out of the plane of the page; shaded arrows show bonds receding behind the plane of the page. (The water molecules can be considered to be tied to the iron ion by weak bonds between the oxygens and the iron.) Ionic radii and bond lengths are to scale.

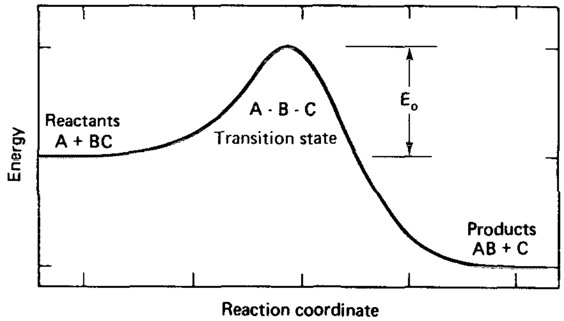
All this was well known, but Libby suggested that a principle formulated decades earlier to help interpret spectroscopic observations could describe how the self-exchange reaction works. The Franck-Condon principle (named for James Franck, who first postulated it, and E. U. Condon, who reformulated it in quantum-mechanical terms) points out that electrons have almost no mass relative to the atom that they're a part of, and so whatever an electron does (which, in the original postulation, meant leaping from one energy level to another within an atom or molecule) has no immediate effect on the much heavier atomic nucleus. If the nucleus somehow has to adjust itself to its new situation—altering its momentum, for example, to compensate for a momentum change in the electron—it takes a moment to catch up. If an electron weighed an ounce, an iron atom would weigh 6,356 pounds. Picture a mouse trying to drag a full-sized pickup truck with the extended cab, dual rear wheels, and the high-rise four-wheel-drive package, laden with five good ol' boys and all their gear for a week-long hunting trip, and you get the idea.

Libby extended this concept to surmise that the solvent molecules can't keep up with the electrons, either. (Although in the case of a water molecule, the poor mouse would only be towing a Ford Pinto.) Now an Fe^{+3} ion is only four-fifths the diameter of an Fe^{+2} ion. The more highly charged an ion, the smaller it is, as its remaining electrons are more strongly attracted to its nucleus. So at the very instant that a travel-minded electron takes wing from an Fe^{+2} ion, the remaining electrons feel the increased charge and plunge toward the nucleus, collapsing the ion to the Fe^{+3} size. Suddenly, the sycophantic solvent molecules find themselves too far away from the ion! Consternation ensues as they scramble to fit themselves into the new regime. Their movement, in turn, triggers a ripple of readjustments in the molecules behind *them*. And it is the amount of energy required to move everybody into their new positions that determines the rate at which the electron jumps. Similarly, at the electron's destination, a diminutive Fe^{+3} ion balloons without warning, throwing *its* courtiers into hasty retreat. This explains why transfers involving naked ions generally occur more slowly than when that same ion is at the center of a complex ion, as in the ferrocyanide case mentioned earlier. The distance between the iron and the cyanides changes by less than one percent, in contrast to the nearly ten-percent change in the distance between the naked iron ion and its six closest water molecules. The solvent molecules beyond the cyanides thus need make, at most, minute adjustments requiring very little energy, and the reaction proceeds quite swiftly.

(Incidentally, both Libby and Franck won the Nobel prize for other work. Franck shared the 1925 physics prize with Gustav Hertz, for discovering that atoms have characteristic ionization energies, confirming the quantum-mechanical postulate that atoms can only absorb energy in discrete amounts. And Libby took the chemistry prize in 1960 for discovering the carbon-14 dating technique now widely used to date archaeological specimens.)

Although Libby published his paper in 1952, Marcus didn't come across it until 1955. Recalls Marcus, "I saw the words *Franck-Condon principle*, and I thought, 'Gosh! I've worked on reaction rates, and I've never seen the Franck-Condon principle used! That's neat! That's *neat!*' And





Above: The contour lines show a piece of the potential-energy surface for the reaction A+BC yields AB+C. The system's potential energy is plotted against the A-B distance and the B-C distance. The two valleys show the stable reactants and the stable products. (Note that the product valley, in the background, is deeper.) As A approaches BC, the system follows the dotted line, and the potential energy increases until the system reaches the transition state—the mountain pass—from which it can go downhill in either direction. Right: Slicing that graph along the dotted line and plotting potential energy against a "reaction coordinate" reflecting both the A-B and B-C distances gives this graph. E_0 is the activation energy.

then I looked more closely at the article, and I felt instinctively that there was something wrong. And so I spent the next month trying to find the correct way of using the Franck-Condon principle." It turned out that Libby had run afoul of quantum mechanics. Libby had assumed, without explicitly saying so, that the electron had simply jumped from one ion to the other. This assumption was wrong. Marcus found that the only way that the electron could "simply jump" to its recipient and arrive there in a permitted quantum state was if a photon of light zapped the electron, punting it into an excited state from which it could legally slide into the other atom. But since electron transfers *do* happen readily in the dark, the law-abiding electrons obviously demanded a different mathematical treatment.

"Now how to treat that problem? In the textbooks of that time, most of the reactions that got detailed theoretical discussion were of the type A+BC yields AB+C. And you could almost *feel* that reaction. You could feel the bond B-C breaking as the bond A-B is forming. You could *sense* it." Theoreticians would draw a three-dimensional potential-energy contour map that plotted the total potential energy of the reacting chemicals versus a reaction coordinate. The potential energy reflected the energy needed to distort the electron clouds surrounding the atoms while they got close enough to each other to react. The reaction coordinate described in a single number the relative positions of A, B, and C. This potential-energy contour plot typically resembled two valleys separated by a mountain pass. The left-hand valley represented the potential energy of the reactants, A and BC, when they were too far apart to sense each other; the deeper the valley, the more stable the reactants. As A closed in on B while the B-C bond began to stretch, the system's potential energy increased—climbing the mountain toward the pass. The higher the pass, the greater the reaction's activation energy, and the slower it was likely to proceed. At the pass, or transition state, the A-B bond was more or less half-formed and the B-C bond about half-broken. From here, the reaction, like a boulder, could either slide down the slope into the right-hand valley to form the products, or tumble backward to the left and revert to the reactants. The deeper the right-hand valley, the more stable the products, and, typically, on comparing a series of similar reactions, the faster the reaction. "But with simple electron transfers, we were faced with quite a different situation. There are no bonds broken or formed, so we couldn't use that particular picture. Instead, we had to look at what coordinates *were* changing, going from reactants to products."

What was changing were the zillion coordinates that described the positions and orientations of all the solvent molecules. (The coordinates of the molecules closest to the ions undergo the largest changes, naturally, and beyond some distance one needn't worry about the others.) Marcus realized that, every now and then, random fluctuations in the orientations and positions of the solvent molecules would put them in arrangements equally appropriate to the products and to the reactants, at which point the electron transfer could occur without violating quantum mechanics or involving photons. The staggering number of calculations needed to figure out how all these molecules were behaving meant that simplifying assumptions were clearly needed. Marcus's first one was to replace all those partially polarized, dipolar solvent molecules with a dielectric continuum—a hypothetical, homogeneous medium that is everywhere polarized, with the degree of polarization decreasing smoothly with increasing distance from the ion, an approximation commonly used when dealing with ion–solvent interactions. Into that polarization, he introduced local fluctuations to represent the nearby solvent molecules' fidgets around their equilibrium positions. The second assumption was that the medium's degree of polarization was directly proportional to the charge on the ions. The third was to cast the problem in terms of "free energy" instead of the potential energy that the theorists working on A, B, and C had used—a thermodynamic subtlety that collapses the zillion solvent coordinates into a single global reaction coordinate. "The 1956 paper used a phenomenological reaction coordinate. I replaced that with a detailed molecular reaction coordinate in the 1960 paper, where I had also replaced the dielectric continuum with a statistical-mechanical treatment for actual solvent molecules.

"The thing is, we couldn't use the standard electrostatics to describe these changes. In standard electrostatics, the dielectric polarization at any point in the medium is dictated by the given charge distribution on the reactants. There's a particular value at every point in the medium, and by solving electrostatic equations, you can find out what the equilibrium dielectric polarization at each point is. But we needed fluctuations. Cumulatively *large* fluctuations due to Brownian motion of the solvent molecules, not little piddly quantum-mechanical fluctuations. So we found a way of calculating the free energy associated with an arbitrary fluctuation, and then, having that fluctuation, we asked, 'What constraint results by imposing the Franck-Condon principle?' In other words, that electron transfer can occur only when the Franck-Condon principle will be satisfied." He was able to express that constraint—that the atoms remain fixed in position during the instant of electron transfer—as a function of three things: the polarization accompanying the charge distribution of, say, the reactants, the free energy of that charge distribution, and the free energy of that *reactants'* polarization but with the *products'* charge distribution.

These calculations required extensive knowledge of electrostatic theory. Fortunately, Marcus had acquired much of the requisite knowledge almost accidentally several years earlier.

These calculations required extensive knowledge of electrostatic theory. Fortunately, Marcus had acquired much of the requisite knowledge almost accidentally several years earlier, as a byproduct of a statistical mechanics course he taught. One Abe Kotliar, a grad student in that class, asked a question about polyelectrolytes—long, chainlike molecules with charges all down their backbones. In the course of trying to answer the question, Marcus immersed himself in electrostatics, going so far as to publish a couple of papers himself. "I had looked through every textbook I could lay my hands on—I think there were 11 of them at the time—and read the relevant parts. The one that was actually the clearest to me for the purposes I needed later on [deriving the Marcus theory] was *The Electromagnetic Field,* by Max Mason and Warren Weaver. And that's a little ironic, because Mason was a professor at Caltech." (Mason was variously member of the board of trustees, chairman of the observatory council, and research associate in astronomy from 1936 to 1949.) The book covered not just equilibrium electrostatics, but dielectrics and polarization in homogeneous media, and expressed everything in very general equations that Marcus was able to apply to his random fluctuations. He found he could generate the fluctuations he needed in slow motion by creating a "reversible path." He'd slowly alter the charges on the reacting ions while letting the solvent atoms—and their electrons—move freely to readjust. Then, at some arbitrary moment, he'd hold the solvent atoms fixed while pushing the charges the rest of the way along to their distribution in the products. The electrons in the solvent molecules would continue to adjust to the shifting charges even though their atoms were frozen in position. This gave the overall system a known, albeit arbitrary, polarization at every point and thus a calculable free energy. Marcus would then do the same thing again, only working backward toward that same moment from the products. Using the calculus of variations and varying the moment when he "froze" the solvent allowed Marcus to find the path with the smallest free-energy change that satisfied the Franck-Condon principle, because the electron transfer happens at that moment when the solvent molecules are frozen.

"I worked very hard, and during the month, at various stages, I thought I had the answer, only to realize that no, I'd made some error or another. Or I got something that looked messy, and I had a feeling it should come out looking simple. I eventually got it in a form where it looked simple, and when I checked it by removing the Franck-Condon restraint, I got ordinary electrostatics coming out of it. And the expressions that I had made physical sense—the larger the ion, the smaller the electric field, and thus the smaller the solvent's reorganization, and so on. Everything just seemed to fit together, and it was at that point that I felt I really had it right. That feeling is hard for me to recapture now, but that was certainly the most exciting moment that I've had. It was really quite a high. I've had other highs—'Gee, I've finally got something,' after working and working and trying all sorts of things, but that was the highest. It really was."

The equation that came out of that month's work is deceptively simple:

$$k = Ae^{-\Delta G^*/RT}$$

where k is the rate constant for the reaction (the actual reaction rate is the product of the rate constant and the reactant concentrations), A is a factor that depends on the specific type of reaction (for example, whether the reactants are freely swimming in solution, or are tethered to each other by virtue of both being parts of some large, rigid molecule), R is the universal gas constant (which crops up in the damnedest places), and T is the temperature. But ΔG^*, the reorganizational free energy of the reaction, conceals quite a bit, as shown in the sidebar at right.

What it all meant is that Marcus could define a single global reaction coordinate for the overall electron-transfer system, including the solvent molecules, in a very precise way—a feat that hasn't yet proven practical for the usual reactions where bonds are actually being formed or broken. This means that electron transfers could be subjected to far more detailed mathematical analysis than other reactions. Furthermore, the system's free energy, when plotted against the global reaction coordinate, becomes a parabola because multiplying out the right-hand side of the equation in the sidebar reveals that ΔG^* depends on ΔG^0 squared. Thus Marcus could draw one parabola for the reactants and the solvent, and another parabola—offset to the right—for products and solvent. The two parabolas intersect at the transition state, giving a picture that bears more than a passing resemblance to the two-valley picture of the A+BC goes to AB+C reaction. But if that potential-energy picture were drawn to include the solvent, it would have to be drawn in a zillion dimensions—one for each solvent coordinate. And the graph would have all sorts of little valleys, local minima where one solvent molecule's dipole or another was in its optimum orientation—an analytic geometer's nightmare. But the two-parabola, free-energy picture provided a simple, intuitive description of the system that allowed Marcus to make predictions that were neither simple nor intuitive. One result that fell out of his mathematics was that the reaction rate for *any* electron-transfer reaction, from rust to respiration, was predictable.

Marcus was originally interested in self-exchange reactions, but he derived his equations broadly enough to cover reactions between two different ions as well. Thus, for an electron jumping from vanadium to a ruthenium hexammine complex (a ruthenium ion surrounded by six ammonia molecules),

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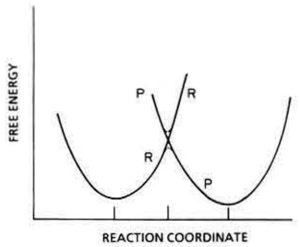


Marcus's two-parabola picture. R is the reactant–solvent parabola; P is the product–solvent parabola.

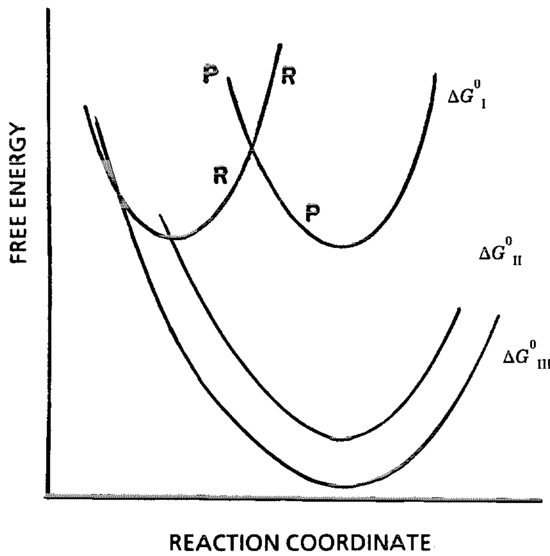
What Lurks in ΔG^*

The reorganizational free energy, ΔG^*, describes what the solvent molecules are up to and the vibrations of the reactants themselves. It is the theory's crucial element:

$$\Delta G^* = \frac{\lambda}{4}\{1 + \frac{\Delta G^0}{\lambda}\}^2$$

where ΔG^0 is the standard free energy of the reaction, a value readily measured experimentally, and λ, the reorganization parameter, is a can of worms in its own right: it represents what the energy barrier to the reaction would be if the products were as stable as the reactants. With the driving force removed, λ contains the factors intrinsic to the atoms involved. There's an "internal" parameter describing how the atoms of the reactants themselves and any molecules or complexes of which they are a part move, taking into account any changes in bond lengths that occur as a consequence of the reaction. An "external" parameter describes the motions of the solvent molecules, and it's here that those zillion coordinates get transmuted into something manageable. This parameter includes properties related to the solvent's dielectric polarization (which in turn depends on two intrinsic dielectric constants of the solvent that between them determine how sensitive the solvent is to electric fields in general), the radii of the reactants (which are assumed to be spherical), and the distance between them. The larger an ion, the farther the solvent molecules are from the bulk of its charge (which behaves as if it were concentrated at the ion's center), and the less strongly a solvent molecule is impelled to readjust; similarly, as the distance between the reactants decreases, they occupy a smaller portion of a solvent molecule's field of view—the molecule is less able to discern a difference in charge distribution and again feels less need to reorient itself.

The inverted effect. Again, R is the reactant–solvent parabola, and P is the product–solvent parabola. ΔG^0_{I} shows a "normal" reaction, with a typical free-energy difference between the products and the reactants. ΔG^0_{II} shows a reaction that is going as fast as it possibly can, because the product–solvent parabola intersects the reactant–solvent parabola at its lowest point. ΔG^0_{III}'s product–solvent parabola has sunk lower still, and the intersection is now climbing the left-hand slope. This reaction has entered the inverted zone, and proceeds more slowly than ΔG^0_{II}.



The inverted effect flew in the face of common sense. For the next 25 years, chemists measured faster and faster reactions in a fruitless attempt to find a reaction fast enough to be slow.

$$V^{+2} + Ru(NH_3)_6^{+3} \leftrightarrow V^{+3} + Ru(NH_3)_6^{+2}$$

proceeding at rate k_{VRu} and with an equilibrium constant K_{eq}, which tells what proportions of the reactants and products will remain when the reaction reaches equilibrium. Then

$$k_{VRu} \cong \sqrt{k_V k_{Ru} K_{eq} f_{VRu}}$$

where k_V and k_{Ru} are the self-exchange rate constants for vanadium and ruthenium hexammine, respectively, and f_{VRu} is a function of the particular reaction whose value is usually close to one. And although reaction rates can be very difficult to measure, especially for fast reactions, equilibrium constants had been measured in their thousands even then. Furthermore, self-exchange reactions had been extensively studied, and many of their rate constants had been published as well. This, therefore, was a concrete prediction that others could verify from existing data. Marcus published this prediction, with others, in another paper in 1960. "But if you just have an equation in a paper, it doesn't mean that people will pick it up. If you apply it to other people's real-life data, and show that it works, that acts as a primer. And I published tests of that and several other predictions from the 1960 paper in the 1963 paper. And ever since, this relation has been very widely tested." This equation is now known as the Marcus cross-relation, and has become a mainstay of chemistry.

Another prediction in the 1960 paper took 25 years to verify, and its confirmation apparently tipped the balance for the Royal Swedish Academy of Sciences. The prediction said that as the free-energy difference (ΔG^0) between the products and reactants increases in magnitude—ΔG^0 actually becomes more negative as the parabola representing the products and the solvent sinks lower and lower relative to the other parabola—the reaction rate should get faster and faster. This was not exactly breaking news—it's exactly what you'd expect. But as the parabola continued to sink deeper, Marcus predicted, the reaction rate would max out and then begin to decline! In other words, once a certain point was passed, the more energetically favorable a reaction was, the slower it would go. The figure at left shows why. As the right-hand (product–solvent) parabola moves downward, the transition state slides down along the curve of the left-hand (reactant–solvent) parabola until the intersection lies at the left-hand parabola's lowest point. At this point, the activation energy—the height of the transition state above the most stable state of the reactants—is zero, and the reaction proceeds as fast as it possibly can. Then as the product–solvent parabola continues to descend, the intersection point begins to climb up the left-hand slope of the reactant–solvent parabola, creating a growing energy barrier once again and slowing the reaction. This prediction, called the inverted effect, flew in the face of common sense. For the next 25 years, chemists measured faster and faster reactions in a fruitless attempt to find a reaction fast enough to be slow. J. R. Miller, G. L. Closs, and L. T. Calcaterra of Argonne National Laboratory finally succeeded, using specially designed molecules that had an electron donor on one end and an electron acceptor on the other, held a fixed distance apart by the rest of the molecule. When the molecule was zapped with a burst of electrons, the donor would catch an electron that, a few billionths of a second later, jumped to the acceptor as a spectrometer recorded its passage.

We have very good reason to be glad that this highly implausible process actually works, because it probably underlies photosynthesis. In photosynthesis, a photon of light hits a pair of chlorophyll molecules, knocking one of their electrons into an excited state. Within three billionths of a second, the electron departs for a nearby pheophytin molecule. About 200 billionths of a second later the pheophytin passes the electron on to a quinone, and the metabolic machinery of the cell is off and running. The process is extremely efficient, ultimately converting darn near 100 percent of the absorbed photons into electric charge. But why doesn't the excited chlorophyll electron simply revert to its ground state? Why don't the electrons leak back from the pheophytin to the chlorophyll? Chlorophyll's ground state is far less energetic than the

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excited one, and therefore much more favorable. And the electron hangs around on the pheophytin for far longer than it sat on the excited chlorophyll, giving it ample opportunity to change its mind. It has been suggested that the reversion to ground state and the transfer back to chlorophyll both lie in the inverted region, making the less energetically favorable leaps to the pheophytin and eventually to the quinone the reactions that actually occur. It's not unlike a skier coming to the lip of a sheer cliff and, thinking the better of hotdogging over the lip and down it, opting to go down the less steep slope on the other side.

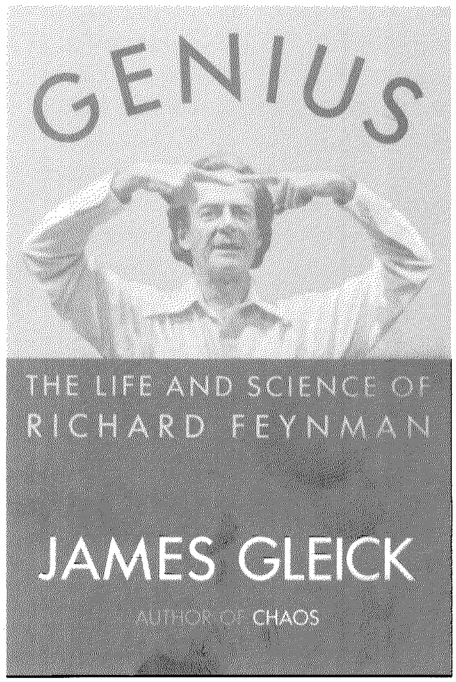
A 1965 paper invoked the inverted effect to explain certain forms of chemiluminescence—the cold light of fireflies and the glow sticks in your roadside emergency kit. Chemists had found that when an electrode in a solution was rapidly toggled between a large positive charge and a large negative charge, the process could create a pair of oppositely charged ions in very close proximity to each other, and the ion pair would emit light. One explanation given at the time was that a local hot spot—hot enough to glow—was created by some unknown mechanism between the ion pair. Marcus instead proposed that the electron transfer to neutralize the ion pair was *so* energetically favorable that it lay in the inverted zone. He speculated that upon electron transfer, one of the ions might go to an excited state instead of the ground state, thus avoiding the inverted zone. The excited state could then emit a photon of light during the return to a lower-energy state.

Reflecting on the Nobel experience, Marcus mused, "There's an interesting point here. In 1952 I wrote four papers related to RRKM theory, a unimolecular theory, and then I looked around and I didn't know what to work on. I didn't want to continue in that, because there were very few experimental data at the time on unimolecular reactions. I thought I would just be spinning wheels, because I wouldn't have anything to tie it to. I don't know if nowadays a young assistant professor can afford the luxury of not doing anything for a whole year! (I did direct some experimental work, however.) I remember only too well a friend of mine, a chap by the name of Frank Collins who was doing some very nice work on liquid-state theory, and every day he'd come downstairs with a new idea he wanted to bounce off me. It went on day after day after day for quite some time—and I didn't have any ideas!" Marcus laughed at the memory. "I wonder if today, with all the pressures of publication and tenure and so on, whether somebody would have the time to let the mind lie fallow like that. I could have continued the unimolecular work and I could have generated more papers, but the fact that I didn't meant that the mind was free—open—for something else. I think that there's an advantage, if one can, in not getting too hooked into one particular thing so much that one stays with it beyond the point of diminishing returns.

"Another thing that helped me a great deal was going out to Brookhaven National Laboratory on Long Island, where there was a fair amount of work going on in isotopic-exchange reactions. I used to go out there about once a month, consulting. I certainly got as much out of it as they did, maybe more," he said with a chuckle. "I worked with Dick Dodson (BS '36 in chemistry), who was a pioneer there, and Norman Sutin. It's *so* important, I think, if one's doing the type of theory I was doing, to interact with the experimentalists. Otherwise you can do something which is far removed from the actual situation. And in turn, when I would discuss the theory with them, it certainly had an effect on the research. Especially on Norman's. He tested various aspects of the theory. The 1963 paper, in which I tested the predictions of the 1960 paper, was stimulated by discussions with him. His knowledge of the results from the reactions involved was truly impressive. Norman is an outstanding individual, and just a splendid scientist. He did things so that once they were done, they were *done*. You could rely on them. I benefited *enormously* from that interaction. Nobody at Brooklyn Poly was doing electron transfer."

"One of the great things here at Caltech is the *tremendous* amount of interaction between faculty, and between faculty and students. I interact a fair amount with Harry Gray. We're making calculations for his experiments [on proteins involved in cellular respiration]. Nate Lewis's work on semiconductors, and his and John Baldeschwieler's work on STM, is stimulating us to try to develop things along those lines. And then there's Fred Anson on his electrodes, Jackie Barton's electron transfer between fixed sites in polypeptides.... About half our work is in electron transfer, and the other half is in unimolecular reactions and intramolecular dynamics, where we have wonderful interactions with Ahmed Zewail next door, with Jack Beauchamp, with Aron Kuppermann in the basic understanding of quantum mechanics; I talk occasionally with Dennis Dougherty and Bob Grubbs about miscellaneous electron transfers, and this list could go on—it's just a wonderful place to be. From every point of view, but especially from that point of view. It makes things vital. And none of it is forced interaction—you want to know something, you find out." □

Books



Pantheon Books, 1992
$27.50
531 pages

A certain former president of Caltech with white, wavy hair told me he was invited to review this book for a prestigious journal, but turned them down. He doesn't like to write book reviews, he said, because there are only two kinds. Either you summarize the book, or you write about yourself. Well, I've been asked to review this book by an even more prestigious journal (*E&S*), and I've decided not to summarize the book. This will be a very personal review.

To start with, I have a confession to make. When this book arrived (Gleick sent an inscribed copy to my wife, Judy, and me) the first thing I did was look myself up in the index and read the parts where I was quoted.

Then I read the rest of the book.

For me, reading this book has been a most peculiar experience. Feynman was my friend and colleague for 20 years. Gleick never met him. So here is this interloper, this stranger, learning about my friend by sitting in dusty archives (the Caltech archives aren't dusty, but who knows what goes on at MIT?) reading dry letters and other people's oral interviews, trying to reconstruct, not merely the life and character of an unseen human being, but one of the most complex and important human beings of this century. How well does he do?

There is at least one mystery he doesn't solve. I can remember sitting at my desk during one of my scientific arguments with Feynman (it was not exactly a level playing field), staring at the back of his head as he stood writing and talking at the blackboard, and asking myself, What the hell is going on in there? Hard as he tries, Gleick doesn't answer that question, nor can we expect him to. A better question, the key question to ask of any biography, is, does he bring the central character back to life? I don't know how others will answer that question, but I can tell you my answer: I can see my friend's face, and I can hear his voice, on every page.

This book is, as the subtitle implies, not only a biography, but also a scientific biography. Gleick has taken on the daunting task of telling us who Feynman was, and also just what he did and why we should care. Not a scientist himself, he has clearly immersed himself in the science (as he did in his previous book, *Chaos)* to the point where he can explain it with clarity and grace. To be sure, some scientists will grumble (have grumbled) that the treatment is superficial and maybe even wrong in places, and some nonscientists will react with their normal reflexes, finding this science, like all science, impenetrable. Don't pay any attention. Having tried my hand at this kind of writing, I can tell you that what Gleick has done is remarkable. Scientists, especially physicists, will generally know exactly what he is writing about, and although they may flinch at an occasional phrase, they will generally appreciate the elegance of his discussions. Nonscientists will find that, unlike Stephen Hawking's book, this one does not have to be left in a prominent place on the coffee table in order to recoup one's investment.

Genius is a fitting tribute to Richard Feynman. Gleick's research is meticulous, his analysis is full of surprising insights, and his writing is fiercely readable. The picaresque, curious (double meaning) character of Feynman's own tales (as told to Ralph Leighton, and nearly everyone else he knew) is recognizable on these pages, but so is the far more important Feynman, the one who left the world richer for having passed through it. First-rate scientific biographies are rare. Einstein and Bohr have had pretty good ones, and my own favorite has been Pearce Williams' s *Michael Faraday.* Months before he died, Feynman thrilled a class of Caltech freshmen by saying (of a famous 1987 celestial event), "Kepler had his supernova, and Tycho Brahe had his. Then 400 years passed. Now I've had mine." Well, Einstein, Bohr, and Faraday have had their biographies, and now Feynman has his.

Lest I forget to mention it: What did Gleick quote me as saying? Among other things, he managed to pick up one of my better lines. About the big red books, *The Feynman Lectures in Physics,* Gleick says,

"They were not just authoritative. A physicist [me], citing one of many celebrated passages, would dryly pay homage to 'Book II, Chapter 41, verse 6.'"

David L. Goodstein
Professor of Physics and Applied Physics
Vice Provost

At the famous "four-level" interchange in downtown Los Angeles, the Hollywood Freeway (center) crosses the Pasadena Freeway, curving off to the northeast.

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