Unleashing the Genius of the Genome to Feed the Developing World[1]

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THE PROSPECT of another agricultural revolution evokes both hope and fear. The first agricultural revolution—the domestication of edible plants—began a long process of narrowing the genome of plants for farming. Centuries of selecting, crossbreeding, and propagating plants for traits such as grain size, pest resistance, food safety, and color have increased and refined our food, but have also inadvertently eliminated countless genes that are important for crops' natural defenses and for our nutrition.

There has been a corresponding narrowing of the global food base. Ninety-nine percent of agricultural production today depends on only twenty-four different domesticated plant species, with three—rice, wheat, and maize—accounting for about two-thirds of the world's food volume. These crop plants have become increasingly distinct from their wild relatives.

The more recent agricultural revolution—the Green Revolution—also involved conventional breeding to enhance the yield of major crops, mainly in areas with plenty of water. This revolution led to agricultural gains in much, but not all, of the developing world and introduced further vulnerability, particularly in the early years, to pests, diseases, and weather as a limited number of cultivars spread across large areas.

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Now we are in the midst of a third agricultural revolution driven by biotechnology—a field that we define as including advanced genetics and genomics, bioinformatics, genetically modified plants, and tissue culture. Will the poorest regions benefit from this revolution? Will the "global commons" of agricultural research and genetic diversity remain open to the world? Will the technology displace more rudimentary forms of crop improvement on which poor societies depend? And, finally, what is the potential of biotechnology for removing some of the most critical constraints in agriculture? Answers to these questions lie at the ethical and pragmatic core of humanity's future.

Some critics see biotechnology as solely a private-sector enterprise favoring a few rich countries and few crops. We disagree. Genetics, genomics, and the supporting computing technology have now advanced to the point of promising egalitarian means of feeding the world. By understanding the genomes of crops, scientists can more effectively tap into the huge reservoir of genetic diversity held in wild relatives of domesticated crop plants and work across a wide array of agroecosystems. Researchers are no longer restricted to the one-size-fits-all approach of technological change characterized by the Green Revolution. As plant geneticists Stephen Goff and John Salmeron note, "The real revolutionary potential [of biotechnology] lies in its power to open up the genetic bottleneck created thousands of years ago when our major crops were first domesticated."

Recent advances in genetics and genomics provide a more coherent understanding of the biology of plants. As a result, new opportunities now exist for extending the science from major crops, such as rice, wheat, and maize, to orphan crops, such as finger millet, cowpeas, yams, and tef. Orphan crops are valued culturally, often adapted to harsh environments, and nutritious. International investments in orphan crop improvement have been negligible to date, even though these crops are critical for feeding the world's most disadvantaged regions.

For an idea of scale, orphan crops (excluding fruits and vegetables) currently cover more than 250 million hectares in the developing world. By comparison, the world's major crops—rice, wheat, maize, and soybeans—are grown on 395 million hectares in developing countries. In sub-Saharan Africa, sorghum and millets are more important than rice and wheat, both in area and in contribution to the diet. Similarly, roots and tubers play a dominant role in Africa, providing more than four hundred kcal per person per day.

Crop improvement in the poorest regions is needed now more than ever. One in seven people still suffers from chronic or acute hunger, and billions of people lack vitamins and minerals essential for a healthy and productive life. Nowhere is the problem more desperate than in sub-Saharan Africa, where the number and proportion of hungry people are forecast to increase. There, three-fourths of underweight children are found within smallholder farming systems, among the landless rural poor, and in marginal and remote areas. Globally, roughly half of the hungry are in farm households, and another quarter come from rural landless households. Providing means to increase the food production and incomes of these households, many of which depend on orphan crops, is an essential step toward alleviating hunger.

Further, these poorest people have the world's highest birthrate, and it has been repeatedly demonstrated that increasing their income leads them to have fewer children. Thus, technology, if applied appropriately, provides a sturdy lever against the problem of population.

THE GREEN REVOLUTION

To understand the promise of biotechnology, it is important to understand the context of the Green Revolution, which arose in response to massive famines and low staple crop yields throughout the developing world in the 1950s and 1960s. Even in regions with reliable water supply and good soil, yields were barely keeping pace with population growth.

Dr. Norman Borlaug, who later received the Nobel Peace Prize for his work, saw that yields could increase substantially with a new plant architecture capable of taking up nutrients and allocating them to the grain (as opposed to stem and leaves). The initial phase of the Green Revolution was all about short and productive plants that would not fall down in heavy wind or rain. As a result of his pioneering work, semi-dwarf varieties of wheat and rice were introduced in the mid- to late-1960s and throughout the 1970s in irrigated regions and in rainfed regions with reliable rainfall. To be most effective, these varieties relied on chemical fertilizers, especially nitrogen and phosphorous. In most agricultural systems of the developing world, crops take up only 30–40 percent of applied nitrogen; the rest is lost to the environment through various pathways. Thus, nitrogen became one of the world's most widespread pollutants. As single varieties were sown over large areas and were cropped more than once a year, pesticide applications also became necessary in many regions and added to pollution problems on- and off-site. The exception was in areas where cultivars with durable host-plant resistance to pests and pathogens were sown, a more common occurrence in the later years of the Green Revolution.

The high-yielding and early-maturing varieties were developed within the International Centers for Agricultural Research, notably CIMMYT (the International Center for the Improvement of Maize and Wheat) in Mexico and IRRI (the International Rice Research Institute) in the Philippines. They were then disseminated and adapted locally by national agricultural research stations in various countries. The process was driven largely by public agencies and charitable foundations investing in research, and it permitted free and unlimited access to the cultivars developed in the international centers.

The private sector had already begun a Green Revolution of its own with the development of hybrid maize in the United States a generation earlier. Later, that crop and development of hybrids of sorghum and millet would pull the private sector, to a degree, into the developing world's revolution.

While rice and wheat were the main crops targeted in the initial phase of the Green Revolution during the 1960s, the technology spread beyond even sorghum and millet to some of the major pulses and root crops, such as cassava, in the 1980s. The later phase of the Green Revolution focused mainly on traits such as disease- and pest-resistance, as opposed to short stature varieties. More modern varieties were actually released between 1980 and 2000 than in previous decades. By the turn of the century, roughly eight thousand modern varieties were released for eleven main crops.[2] These varieties were released in more than one hundred countries by about four hundred public breeding programs. The dissemination of the technology by the international agricultural centers was truly impressive. More than 35 percent of the modern varieties released and adopted in the developing world during the Green Revolution were based on crosses made at these centers.

Unfortunately, not all developing regions benefited equally from the Green Revolution, and sub-Saharan Africa was one region that was largely left behind in the process. For most crops, researchers first developed a plant prototype for each agroecosystem to serve as a platform for local adaptation, and then bred for locally required traits, such as resistance to specific pests and diseases. This second step was particularly important for the technology's widespread adoption and success. Economists Robert Evenson and Douglas Gollin note that in the early period of the Green Revolution, "national and international programs may have sought to 'short-cut' the varietal improvement process in Sub-Saharan Africa by introducing unsuitable varieties from Asia and Latin America, rather than engaging in the time-consuming work of identifying locally adapted germplasm and using it as a basis for breeding new varieties." A principal challenge for widespread crop improvement in sub-Saharan Africa has been and continues to be the vast heterogeneity of agroecosystems.

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[2] These crops included rice, wheat, maize, sorghum, pearl millet, barley, lentils, beans, groundnuts, potatoes, and cassava.

Adoption of modern varieties did occur in sub-Saharan Africa later, although it never revolutionized agriculture on the continent. Yield increases did not lead to major gains in overall production, and the role of modern varieties in production growth was relatively small. Agricultural output growth between 1980 and 2000 was based almost entirely on the expansion of area under cultivation.

Given the regional disparities of the Green Revolution, how should one weigh its success? Yes, it was enormously successful for some crops and in some areas, particularly those in favorable ecological zones. It often led to wanton irrigation, however, and relied on chemical inputs that were expensive for poor households and often damaging to the environment. It also failed to reach the poorest farmers, many of whom grow orphan crops or live in marginal areas where irrigation is not possible. Where policies favored large-scale producers, small farmers were often driven off the land by more “efficient” farming, leaving them no refuge except the shantytowns that now ring every city in the developing world. The Green Revolution developed the tool of increased yields, but once scientists and development specialists had that hammer, they began to see all problems as nails.

The Biotechnology Revolution

Conventional breeding—the core of the early Green Revolution—is to some extent a hit or miss process. Without understanding the genetic structure within the plants, farmers and crop breeders can only rely on visible characteristics, such as plant height, grain quality, or pest resistance, for selection and crossbreeding. Despite its lack of precision, however, conventional breeding has worked extremely well over the millennia to improve yields and produce desirable plant types for human consumption. It has also “turned off” a number of genes, making them dormant, while other genes have been “turned on.” Until recently, the genetic information lost during the continuous process of selection and breeding has essentially remained a mystery.

With biotechnology’s new tools, scientists are now able to augment the process of field-based selection with a system of genetic identification and marker-assisted breeding based on precise information on where genes are located in the genome, and how they function in the plants. Mapping genes, marking genes for breeding purposes, moving genes between organisms, and turning genes on and off are all part of the process we refer to here as the biotechnology revolution. Biotechnology encompasses far more than genetically modified organisms (GMOs), which are typically the focus of discussion and debate.

The GMO debate

In the 1990s, GMOs were hailed in the U.S. as a technological miracle that would save farmers money, lower food prices, and reduce environmental damage unintentionally caused by the Green Revolution through chemical input use and irrigation. Scientists showed that they could raise yields and create durable resistance against pathogens by adding DNA from another species into the genomes of various crops—a process known as transgenesis. As a result, farmers could lower costs, and environmental damages from chemical use and loss would be reduced. Opponents of the technology, on the other hand, call it "Frankenfood"—a contaminated food product over which consumers have no control. Moreover, the ecological risks of transgenic technology to wild plants and neighboring crops have remained a contentious issue.

The role of GMOs in solving the hunger problem has risen to the highest level of ethical debate. Shipments of food aid containing genetically modified crops have been rejected by famine-stricken countries in Africa. The European Union has all but outlawed transgenic crops, promoting a global trade war that is costing U.S. farmers billions of dollars in lost exports, and often leaving its African trading partners with little choice but to ban GM crops as well.

In September 2004, the Pontifical Academy of Sciences and the U.S. embassy to the Holy See convened a conference on "The Moral Imperatives of Biology." The Vatican remains undecided on the issue, despite significant opposition to GM crops from within the Catholic Church. Others at the conference viewed GMOs as not just a scientific innovation, but also a moral leap forward for mankind. They claimed that the worst form of cultural imperialism is to deny poor countries the opportunities that the industrialized world has to take advantage of new technologies to improve health, nutrition, and incomes.

The Interacademy Council, an international body that draws on the expertise of ninety national science academies, recommends a broad-based approach to solving agricultural problems in the poorest regions of the world, particularly sub-Saharan Africa, and endorses the use of GM crops. The Millennium Project's Hunger Task Force, commissioned by the U.N. secretary general, agrees that GM technology has opened up new opportunities that could feed starving people in Africa, particularly projects involving drought-tolerant maize and disease-tolerant bananas. But they note that GM technology will not remove many of the present barriers to feeding the poor, such as a lack of credit, infrastructure, or seed markets.

The sad fact is that GM technology may have raised, not lowered, some barriers to feeding the poor. Unlike the Green Revolution, most

GM technology is owned and patented by a handful of multinational agriculture seed and chemical companies. The dominance of the private sector raises concerns that poor farmers will not have access to GM technology—because appropriate innovations are not available for their crops and ecosystems, because they are patented, or because they are too expensive. The private sector often lacks business incentives to invest in orphan crops and poor countries where markets are relatively small.

In 2002, roughly three-quarters of the area seeded to transgenic crops was in industrialized countries (68 percent in the U.S. and 6 percent in Canada), and the remaining area was in developing countries with advanced agricultural systems (22 percent in Argentina, 3 percent in China, and less than 1 percent in India and Brazil combined). Soybeans accounted for 62 percent of the area sown to transgenics, with the remaining area planted to transgenic maize (21 percent), cotton (12 percent), and canola (5 percent). Three-quarters of the GM technology applied was for herbicide tolerance (mainly Roundup Ready herbicides), and the rest was devoted to Bt stem-borer resistance (achieved by inserting a gene from a bacteria) or a combination of the two. If one defines biotechnology strictly by GMOs, then the critics are correct: the technology is largely controlled by the private sector and currently benefits few countries and few crops, mainly in the industrialized world.

Given the nature of GM technology and its private ownership, several key questions arise. Can, and should, this technology be shared with poor countries? If so, how, and at what cost? Should developing countries serve as sites for experimental testing of GM products? What biosafety measures should be put in place before the technology is transferred? These questions are debated not only within the industrialized world, but also in Africa and other parts of the developing world. Luckily, advances in genetics and genomics are creating alternatives to GM technology that do not involve foreign gene insertion or patents. As Robert Goodman, professor of plant pathology at the University of Wisconsin and former head scientist at Calgene, concludes, "The public argument about GMOs will soon be a thing of the past. The science has moved on."

Advanced genetics and genomics

The real revolution lies below the surface and is based on knowing the location and function of both active and dormant genes. Over the past decade, scientists have discovered that our major crops are full of silent genes. Rather than inserting, for example, a bacteria gene for pest defense, it is often possible simply to turn on the plant's innate ability to defend itself. Advances in genomics and information technology—

from processing power to databases and storage—have given crop scientists not only the ability to create card catalogs detailing the library of traits expressed in individual varieties, but also the techniques to turn them on universally. With this technology, it is possible to recover knowledge and use of plants' genetic diversity that are essential for crop growth and protection. Rather than adjust ecosystems to meet crop requirements—as occurred in the Green Revolution—by requiring water, fertilizer, and often pesticides, scientists can now work with diversity in the species to grow crops that fit local conditions.

This knowledge has resulted from the most basic type of molecular research on genomes for major crops in industrialized countries. Without aiming for specific applications at the outset, scientists at both public and private institutions have mapped genomes or important DNA sequences for widely consumed crops, such as rice, maize, and soybeans, and for model species, notably *Arabidopsis.* They have identified and mapped a few thousand trait-controlling loci in the DNA of various domesticated cereals, and in the process have found a surprisingly high degree of correspondence between the different genomes. Different plant species within the cereal group have different versions of the same genes at a given position or locus in the genome, but the order of loci is conserved to varying degrees across even distantly related crops.

This correspondence, known as synteny, allows scientists to think of certain groupings of crops as having a single genetic system—particularly species within a given family, such as the grass family that includes the world's most important cereal crops. As a result, discoveries of gene location or function in one cereal crop promise to provide clues to understanding and improving other cereal crops. Given the similarities among crop genomes, it is possible that research on major crops or model species could benefit a substantial number of related orphan crop species in the same families. For example, research on the rice genome could lead to improvements in millet and tef production, and research on tomatoes could benefit indigenous vegetable production in Africa and Asia.

One of the most powerful tools in the emerging biotechnology toolkit is marker-assisted breeding, which allows scientists to flag particular regions of the chromosome that control a given trait in a crop, such as seed size, flesh color, or salt tolerance. This technique is relatively straightforward for traits conditioned by single genes with large effects and showing simple inheritance. These traits, called qualitative traits, include some resistances to diseases and insects and some traits controlling plant growth. Genes controlling qualitative traits are also relatively easy to identify in conventional breeding programs. There are cases, however, in which markers are particularly beneficial even for these genes; for example, when a disease resistance gene must be identified, but the pathogen is not present at the breeding site, or when a gene is to be selected at the seedling stage for a trait that is expressed only later in development.

Most important traits, however, are governed by many genes acting together, each having relatively small effects. These traits—called quantitative traits—include, for example, tolerance to drought and nutrient-deficient soils. They have been difficult to understand and manipulate in conventional crop breeding programs. Gene sequences contributing to the expression of these traits are now beginning to be mapped and cloned through marker-assisted genetic analysis, paving the way for breeding programs that could remove some of the most serious constraints on agricultural production in marginal areas.

With markers, much of the early-stage breeding can be done in the lab, saving the time and money required to grow several generations in the field. Once breeders have marked a trait, they can use traditional breeding tactics like tissue culturing—growing a snip, sometimes a single cell of a plant in a nutrient-rich medium until it is strong enough to survive on its own. Another technique for culturing is embryo rescue, which allows breeders to crossbreed distant relatives that would not normally produce viable offspring; after fertilization, the premature embryo is extracted and fostered in the lab. A third technique—anther culture—enables breeders to develop a complete plant from a single male cell. The science behind some of these techniques makes transgenics look unsophisticated.

Marker-assisted breeding provides an approach that can be applied to a broad range of crops and agroecosystems. It is an approach that does not require foreign gene insertion and can be independent of chemical inputs. The success of markers to date has been crop-dependent; nonetheless, once the basic science is developed, the techniques themselves are straightforward and can be, and are being, carried out in thousands of relatively primitive labs around the world. It is appropriate technology.

Many future improvements in crop productivity and quality are likely to come from tapping the genetic wealth of domesticated crops' wild ancestors by breeding useful traits back into the modern varieties. Pioneering experiments by Steven Tanksley and Susan McCouch of Cornell University on rice and tomatoes have mapped the genetic diversity available in wild relatives of domesticated plants, and have shown that the wild varieties' most valuable resources are not always visible. Crosses of domesticated rice and low-yielding wild rice have generated yields as high as 30 percent greater than the most productive parent, while crosses of domesticated tomatoes and green wild tomatoes have generated plants with fruit more red than either parent.

The genetic variety in wild relatives of the world's crop plants is only beginning to be explored. For instance, an estimated 80 percent of the total allelic diversity of rice and tomatoes remains untapped. Because many desirable traits in wild relatives are not expressed visibly in the plant, marker-assisted breeding provides a critical tool for exploring the true potential of agriculture.

Meanwhile, developing on another front is a series of highly sophisticated techniques that take advantage of the natural shakeup in the genome that occurs during sexual reproduction. Scientists are finding that subtle tweaks applied during reproduction can cause gene switches to reverse, turning on silent genes to gain new traits. Some of these techniques are close to bearing practical fruit.

How applicable will these scientific advances be for developing-country agriculture and food security? Will scientists in poor countries play a role in developing and using the science? What will be the cost of transferring this technology to orphan crops? A key issue in answering these questions is to identify the correct balance of scientific investments between major and orphan crop development in poor countries so that the spillover effects from major crop research are maximized, and scientific foundations for orphan crop research are thus ensured.

Unleashing the Genius to Improve Food Security

Advanced genetics and genomics offer a tool for equitable agricultural development. The question remains, however, will poor countries receive the investments and institutional support needed to benefit from the emerging science? From the donors' perspective, do such investments have a decent pay-off in terms of food security objectives?

A few key foundations and public development agencies are allocating significant funds to orphan crop development and biotechnology transfers to poor countries. The McKnight Foundation's Collaborative Crop Research Program has a $50 million program designed in large part to transfer science from major to orphan crops and to train scientists from the developing world in advanced genetics and genomics methods. The Rockefeller Foundation spent $100 million on research and on building the developing world's capacities for research on rice. It has just launched a new program for biotechnology and crop improvement in Africa. As part of this investment, it provides support to the African Agricultural Technology Foundation (AATF), whose primary function is to match biotechnology innovations with local needs in African countries. Specifically, the technology foundation helps design relevant templates, protocols, and procedures to lower transaction costs of applying biotechnology to major and orphan crops in the region. Dow, DuPont, Monsanto, and Syngenta have agreed to provide seed varieties, patent rights, and laboratory knowledge to African countries through AATF. The international agricultural research centers, which have traditionally focused on major crops, have also now decided to devote additional funds to orphan crop development. Finally, the biotechnology programs being developed and promoted in Dutch, Swiss, and U.S. aid agencies are contributing to progress in orphan crops. Simple economic calculations show that the pay-off to investments in biotechnology in poor countries can be large, particularly if there are spillovers from major crop to minor crop research (see box).

While the investment picture is beginning to look more promising in this area, the issue of access, patents, and shared technology remains a challenge. Richard Jefferson at CAMBIA (the Center for the Application of Molecular Biology to International Agriculture), located in Australia, is a major leader in the effort to solve this problem. His vision is to promote "distributed development" by providing free access to technology for the developing and developed world. The idea of distributed development is to have charitable foundations like those mentioned above, which have paid for most of the world's public-interest crop science, fund a network of researchers to develop platform technologies and pro-

REAPING THE RETURNS

With synteny among the cereals, it is possible to use comparative genomics within the grass family to identify orphan crop genes with powerful traits, such as insect and disease resistance, based on discoveries in the genomes of major crops. As a hypothetical example, an investment of \$500,000 per year for ten years (\$5 million total) in marker-assisted breeding for blast resistance in finger millet could be successful, particularly given the gains made in identifying genes and gene combinations for blast resistance in rice. Neck and finger blast typically reduce finger millet yields by 35 percent or more. Successful breeding for blast resistance could increase average yields from 1.3 ton/ha currently to over 1.75 ton/ha. A more conservative estimate of potential success would be to achieve a 15 percent gain in yields from resistance (to 1.5 tons/ha on average) on one-half of the total area. Given an area of 3 million ha planted to finger millet in India, another 1 million ha in Africa, and a price of \$96/ton, the gross annual benefits would be more than \$38 million globally (almost \$29 million per year for India and \$9 million per year for Africa). Even if large costs were incurred to move the technology into the field (e.g., \$25 million initially, and a smaller long-term flow each year), the net pay-offs would still be large.

vide free licenses to public and private scientists to use those technologies. Commercial, for-profit end products would be encouraged, but the basic technology would remain in public hands. CAMBIA's mission of unlocking important technologies that remain dormant in labs and greenhouses due to patent restrictions is akin to the computer revolution—like Microsoft's proprietary code's giving way to open source software, most notably Linux. The process is decentralized, networked, and accessible, but also powerful in its ability to promote innovation.

Other efforts are under way to organize access to existing and emerging intellectual property within the public sector. A consortium of U.S. universities called PIPRA (Public-Sector Intellectual Property Resource for Agriculture) is now pooling intellectual property database information and may even use its collective intellectual property in agricultural technologies for humanitarian use in the developing world.

The elimination of intellectual property barriers and the free availability of DNA sequence information on the Internet will assist in the rapid transfer of information from advanced laboratories to laboratories in poor countries. In order to have a significant impact on crop improvement, however, scientists in developing countries must be trained to take advantage of the knowledge and be equipped with adequate laboratory space and appropriate tools. In many poor regions, reliable Internet hookups—or even the simplest computer equipment—are not available. Investments in basic equipment and training are a necessary condition for advanced technology transfer.

Moreover, success in the laboratory or experimental plot still needs to be integrated into a much broader scientific process in order to benefit rural communities. A technological continuum exists for germplasm improvement, which ranges from simple selection techniques, to conventional breeding approaches with farmer participation, to developments in GM technology, marker-assisted breeding, genomics, and bioinformatics in advanced laboratories. Unfortunately, the continuing decline in funds for practical crop improvement, particularly in the international public sector, results in a fair amount of investment in research, and a weak application to practical problems. Applying molecular techniques to basic research in plant biology has led to a much deeper understanding of the genetics of key traits, but not always to a clear idea of how plants can be improved.

The balance between field-based and basic (lab-based) science raises interesting questions of human capital development and the opportunity costs of moving toward high-tech science. There are a surprising number of highly trained scientists in poor countries, people who have received graduate degrees from universities with advanced laboratories in industrialized countries, and in developing countries where the scientific capacity is high (e.g., Brazil, China, India). Many such scientists return to their countries to work on pressing issues in agricultural science and development. But many others among them stay abroad, where the professional opportunities and pay are higher. Brain drain likely will continue, but the emerging technologies could well tip the balance toward the developing economies.

The new plant science is by its nature diffuse, a platform of tools that allows local scientists to develop local solutions. Many poor countries already have laboratories capable of doing this work, but the centralized nature of earlier crop research has drawn the best scientists to those centers. Spreading the important work to local labs may well pull scientists in that same direction, a speculation confirmed by many of our interviews with young, developing-world scientists.

Supporting this trend is information age technology. Young scientists have told us repeatedly that Internet access allows them to collaborate with colleagues around the world, removing the sense of isolation that has often plagued researchers in the poorer countries. To a scientist, the sense of being involved in important and prestigious research is often as great a draw, or even a greater draw, than a six-figure, developed-world salary.

Will Biotechnology Feed the World?

Appropriate use of biotechnology depends on the agricultural problem at hand, the biological properties of the crop, and the economic and social infrastructure that supports crop research. The best chances for harnessing the gains from biotechnology exist when the science is integrated into breeding efforts, farm management, and seed production and distribution. Even with integration, the benefits from advanced science depend critically on the institutional, human capital, economic, and political context of the recipient countries. Are poor countries likely to gain? Will biotechnology help to alleviate hunger in any significant way?

Our view is that scientific advancements in the fields of genetics and genomics are on the verge of something truly enormous. Plant genomes carry age-old records that reveal the complex manner by which nature manages itself. Scientists are now cracking these codes, and the information they provide has practical use for the improvement of both major and orphan crops. Success in tapping this information effectively will not be automatic, however. There will not be a sudden surge in agricultural productivity in the world's poorest countries—no big bang. Instead, the technology is likely to seep in from many directions, through multiple crops, through a process of looking forward and looking back. Now is the time, early in the process, for the development community to lever this revolution toward equity and social justice.

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