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Innovations in science and technology have a critical impact in fields related to sustainable development, such as health monitoring, energy management, agricultural productivity, pollution control, food processing, and sanitation upgrades. Calestous Juma, chairperson of the UN Millennium Project Task Force on Science, Technology and Innovation emphasized that "it is inconceivable that the UN Millennium Development Goals can be achieved as planned by 2015, or even that significant gains can be made in meeting health and environmental concerns, without a focused policy for science, technology, and innovation."[1] The most recent addition to our science and technology toolkit is nanotechnology, the study, design, creation, synthesis, manipulation, and application of functional materials, devices, and systems through control of matter at the nanometer scale—that is, at the atomic and molecular levels.[2] However, despite rapid advances of nanotechnology in fields such as consumer electronics and cosmetics, there is no coherent program linking nanotechnology to global developmental challenges.

Nanotechnology, if exploited appropriately, can bring tremendous benefits to developing countries. Our group at the Canadian Program in Genomics and Global Health has extensively studied the role of nanotechnology for the devel-

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oping world. In collaboration with an international panel of experts, we conducted a foresight study in 2003, which identifies and ranks the ten nanotechnologies most likely to benefit developing countries in the 2003-2013 period.[3] To evaluate the impact of these ten nanotechnologies, we mapped them to the UN Millennium Development Goals, a set of eight quantifiable development targets that all UN member states have committed to achieve by 2015.

The successful application of nanotechnology toward sustainable development challenges depends upon the skillful collaboration between nations, in particular between developed and developing countries, which we refer to as *nano-diplomacy*. This article will show that nano-diplomacy must go beyond international treaties and conventions in order to create bottom-up collaboration between governments, industries, civil societies, and academia in both the developed and the developing world. The success of linking nanotechnology to development applications also depends on how effectively developing countries address the issues of safety standards, intellectual property, and public engagement.

Local Responses to Nanotechnology. To address local needs, developing countries need a policy that is focused on technology *innovation*, and not merely technology *transfer*. As *Forbes Magazine* publishes another year's "Top Ten Nanotech Products"—featuring foot warmers, golf balls, and personalized skin care—developing countries need their own nanotechnology innovation systems to create products most responsive to local priorities.[4]

Local nanotechnology initiatives present an encouraging picture. Our survey of nanotechnology activity in developing countries highlights many cases of successful partnerships between local industries and scientists and researchers to develop locally relevant nanotechnology products.[5] For instance, nanotechnology has been a priority of the Chinese government since the late 1990s. Its national nanotechnology plan has strong funding from programs like the National 863 Hi-Tech Research and Development Plan and the Knowledge Innovation Program. China has also established numerous national centers for nanotechnology research and development, including one currently under creation at Tsinghua University, located near the Tsinghua Science Park.[6] This Science Park is a national "innovation model" that links industry and researchers in order to accelerate and sustain innovation in strategic core technologies, including nanotechnology. As a result of its focused efforts, China has over 800 nanotechnology-related companies, and the country is a patent leader in this field.[7] South Africa has also adopted a national nanotechnology strategy to address industrial and social priorities in the areas of health, water, and energy through a focus on nanotechnology applications.[8] Thailand's National Nanotechnology Center, located in the Thailand Science Park in Pathumthani, is an autonomous body under the government's National Science and Technology Agency and aims to apply nanotechnology for economic and human development.[9]

Some have wrongly argued that nanotechnology will upset developing-country export markets that rely heavily on agricultural products and raw materials like rubber, since the demand for these primary commodities will decrease as nanotechnology produces cheaper laboratory-created substitutes. The result will be that nanotechnology will displace poor agricultural, factory, and mine laborers, among others.[10] On the contrary, advances in science and technology have inevitably brought about the automation of manual tasks. Thus, the decrease in manual labor is a natural consequence of any technology, not just nanotechnology. In both developed and developing countries, the workforce has necessarily adapted to the changes derived from successive waves of technology. Local innovation offers the best approach to maximize the benefits of nanotechnology for the developing world, and these potential gains warrant a more appreciative outlook toward nanotechnology's role.

Developing countries need a focused policy on technology *innovation* and not merely technology *transfer*.

Local Benefits to Local Responses. Developing countries derive unmistakable benefits from nanotechnology. First, nanotechnology's advances will improve the welfare of the world's poorest and sickest. For instance, agricultural applications of nanotechnology such as nanoporous zeolites can increase soil fertility and crop productivity, while novel devices like nanosensors can monitor crop health.[11] Nanotechnology can protect against the devastating consequences of crop failure in developing countries, including malnutrition, famine, and displaced and impoverished farmers, which represent a severe strain on a country's limited resources. Since 2001 researchers from University of Brazil, the Federal University of Goiás, and the Federal University of Rio de Janeiro have been developing nanomagnets for cleaning water contaminated by large-scale oil spills.[12] The Chemistry Institute at Brazil's State University of Campinas has been developing nanobiotechnology applications, including the use of nanoparticles in drug delivery systems.[13] The India-based non-governmental organization (NGO) Nimbkar Agricultural Research Institute undertakes innovative science and technology programs to improve the quality of life of the rural poor in India and is currently investigating the use of nano-engines that operate on biomass-derived fuels to produce efficient and transportable lighting sources for rural communities. Once this technology is established, "cost reduction processes and creative financing mechanisms for its availability to rural poor can be designed."[14] Research in Thailand includes nanofiltration systems for water treatment and sanitation and the fabrication of prototype solar cells using nanoparticles as electron acceptors.[15] Hence, nanotechnology can be employed to address local needs in developing countries.

Second, nanotechnology will also create more opportunities for local scientists and researchers and will help accelerate the transition of innovating developing countries toward robust knowledge-based economies. South Africa's Department of Science and Technology has spoken of overcoming the "innovation chasm" in order to move away from technological dependency.[16] This shift should move from the bottom up and should include a special emphasis on basic and interdisciplinary science education. The universities of Madras, Mumbai, and Kolkata in India have established a collaborative degree program in cutting-edge nanoscience and nanotechnology.[17]

However, the economic impact of nanotechnology will depend upon the economic development stage of a country. Comparatively advanced countries such as China and India have a greater critical mass for nanotechnology exploitation than less developed countries in South Asia and Africa. Given the limited resources available to each country, the trick is to prioritize applications that promise the greatest benefit for the greatest number of people.

Nanotechnology will help accelerate the transition of developing countries toward robust knowledge-based economies.

Challenges for Developing Countries.

The Challenge of Managing Intellectual Property. Benefit-sharing between developed and developing countries in the commercialization of nanotechnology products is necessary. Consideration must be given to the best ways to harness intellectual property (IP) for the development of nanotechnology, bearing in mind that patents from universities, companies, and the military might inhibit research and development efforts in less industrialized countries. With respect to IP rights, an inherent tension exists between providing incentives for innovation and promoting wide and easy access to the resultant technologies, especially if the technologies are important to save lives or to help large numbers of people. While such issues are complex, it seems prudent to avoid undue concentration of resources in a few hands, as this leads to "patent thickets," which actually impede research and development.[18] Patent pools, patent clearinghouses, and open-source types of approaches that have been successful in the information technology sector may be solutions to prevent this problem. In the field of biotechnology research, the African Agricultural Technology Foundation has negotiated royalty-free licensing and sublicensing with technology patent holders from private companies, public-private partnerships, and NGOs to help developing-country research institutes access patented agricultural technologies.[19] Successful nano-diplomacy must address the effects of IP regimes on the developing world.

The Challenge of Incorporating the Private Sector. Private-sector involvement is a key factor in moving from knowledge to product.[20] India's national nanotechnology initiative involves more than thirty research and development institutes to identify nanotechnology products with potential for commercialization. The private CranesSci MEMS Lab, located in the Indian Institute of Science, advocates the establishment of nanotechnology centres inside research institutes with seed funding from private companies. According to this institution, engaging local private enterprise in India's nanotechnology research will strengthen domestic capacity, attract and retain highly skilled national and international researchers, and ensure the longevity of product-driven research centers.[21] In Brazil the University of Sao Paulo established the incubator Nanocore Biotechnology[22] as an on-campus spin-off company from a university group's research on biodegradable nanoparticles for encapsulation of pharmaceutical agents. The South African Nanotechnology Initiative (SANi) aims to coordinate university researchers, industrial companies, and government-science councils to catalyze multi-sectoral nanotechnology advances.[23]

The Challenge of Managing Risks to the Environment and Human Health. Although nanotechnology can contribute to human welfare, particularly in developing countries, not all of the effects of nanomaterials in the environment are known. For example, nanoparticles could accumulate in different organisms, become incorporated in living tissue, and move up the food chain in a process known as bioaccumulation. A study on largemouth bass found elevated levels of oxidative deterioration of lipids in the brains of fish that were exposed to water-soluble fullerenes, which are hollow carbon structures that are used in many nanotechnologies.[24] Another concern is the possibility of hazardous exposure to nanomaterials in industrial and scientific workplaces. The main routes of internalization are inhalation, ingestion, and absorption. Animal studies have found that inhaled nanoparticles can be selectively transported into the brains of mammals via the olfactory nerves.[25] Another study has found that nanotubes can induce inflammatory lesions in the lungs of mice.[26] While these studies suggest that nanoparticles may be toxic, animal models alone are not sufficient to predict risk effects of nanoparticles in humans.

Clearly, more and better information is needed to predict the effects of nanotechnology on environmental health and safety. A research group at the University of Toronto is currently monitoring developments in the toxicity of quantum dots, with the aim of creating a database of nanotoxicity studies and developing policy options for converging technologies. The Center for Biological and Environmental Nanotechnology at Rice University is engaged in research on how nanomaterials interact with biological systems and affect biochemical and cellular processes.[27] The International Council of Nanotechnology recently launched an online catalogue of scientific literature on the environmental, health, and safety implications of nanomaterials so that researchers, industry, government agencies, and the public can access the most current information for assessing the safety of nanoparticles.[28] Developing countries must have efficient and inexpensive measuring and monitoring devices for workplace exposure to nanomaterials. Novel protective gear will probably be necessary to avoid risks related to the handling of these substances.

The Challenge of Managing Public Engagement.

Recent studies on the public perception of emerging nanotechnologies suggest that the public desires more information on nanotechnology's promises and risks and wants increased testing on environmental and health effects.[29] The studies encourage industry to listen to the public and to recommend mechanisms to integrate the public into national policy decision making. One way to increase public participation in science and technology is to convene citizens' juries, representative of a diverse subset of the population, that then provide recommendations for the future direction and regulation of nanotechnology. One such effort is NanoJury UK, which brings together twenty randomly chosen people to engage in discussions of the societal impacts of nanotechnology and to provide a potential vehicle for the public's views to influence policy decisions.[30]

Greater public information means greater preparedness to make rational assessments instead of relying on knee-jerk reactions and gut feelings. Engaging youth in discussions of emerging technologies is key to developing an informed future voting population. In 2002 we developed *Engage: Stem Cells*, a curricular unit for Canadian high school students to debate the ethical and governance issues of stem cell technology. Based upon this highly successful strategy, we are currently developing NanoEngage, a public outreach tool to foster greater social awareness regarding nanotechnology's potential to improve lives in developing countries.

Overly apprehensive views and exaggeration of the risks can stall serious progress in nanotechnology and can diminish the health, environmental, and economic opportunities for developing countries. Addressing legitimate concerns and allowing developing countries to weigh the risks and benefits for themselves will allow responsible development of nanotechnology and will pave the way toward public acceptance. Nanotechnology should be given the opportunity to create real, tangible benefits for the developing world—such as for the 50 million people in Bangladesh at risk of arsenic poisoning and for the 4 million affected by the earthquake in Pakistan—before Michael Crichton's novel, featuring life-destroying nanoscale robots, makes it onto the big screen.[31]

International treaties and conventions may not be well suited to promoting the global benefits of a rapidly advancing field of science and technology.

Components of Nanodiplomacy: The Role of Industrialized Countries.

Global Challenges. One way to accelerate the application of nanotechnology for developing-country needs is to summon the world's best scientific minds to address grand challenges, using the model employed by the FNIH/Bill and

Melinda Gates Foundation's Grand Challenges in Global Health. A grand challenge is a call to arms for investigators to channel their efforts toward a specific scientific or technological breakthrough that will overcome one or more significant development challenges. An initiative entitled "Addressing Global Challenges Using Nanotechnology" could draw from the top ten nanotechnology applications we have already identified for developing countries to construct a plan of action for mobilizing the international community. Funding for this initiative could be tied to industrialized countries' official development assistance programs, or it could be part of discrete funding for science and technology assistance.

Collaboration. North-South collaborations that link developed- and developing-country scientists, industries, and governments will not only facilitate the international harmonization of regulatory frameworks, but will also promote awareness of the needs and opportunities for the poor with respect to nanotechnology. South-South collaborations will become increasingly relevant as developing countries learn lessons from the successes and failures of other developing countries in building strong nanotechnology sectors.

Global Governance. A global strategy is needed to assess and promote nanotechnology for development. While traditional governance models tend to focus on risks and restrictions, a more holistic model should include a focus on innovation and the enormous potential of nanotechnology to address global challenges. Among the issues to be addressed are the following: How can nanotechnology be used responsibly? Which applications ought to be given priority? What policies are needed to develop capacity and ensure that the benefits of nanotechnology reach those in greatest need? How should regulatory regimes be developed and implemented?

Choosing an appropriate governance model for mobilizing international action in nanotechnology is crucial. International treaties and conventions may not be well suited to promotion of global benefits of a rapidly advancing field of science and technology. They are often slow to be negotiated and ratified and may suffer from poor adherence once they come into force. A flexible global network of representatives from government, academia, industry, and civil society could serve as a forum for international dialogue between the public and policymakers to shape institutional decisions and discuss policy options.[32] Inclusive and equal participation of diverse sectors such as civil society and industry would facilitate collaborative strategies for managing risks in order to promote the global benefits of nanotechnology. Existing networks, public-private partnerships, and coalitions working to establish worldwide capacity in science and technology, including the InterAcademy Council and the New Partnership for Africa's Development (NEPAD), could play a significant role in this global network.

Conclusion. Given the emerging global consensus on the role of science and technology as a critical instrument of development, industrialized countries should take the lead to ensure that its advances benefit both the rich and the poor. Indeed, science and technology is becoming an integral element of foreign policy and international relations. Canadian Prime Minister Paul Martin has committed to devoting no less than 5 percent of Canada's research and development spending to address developing-world challenges.[33] In a 2002 speech to the National Academy of Sciences, former Secretary of State Colin Powell noted: "You don't have to...be Secretary of State to survey the twenty-first-century terrain and see that science and technology must inform and support our foreign policymaking in this challenging world that we live in. Whether the mission is...creating conditions for sustainable development, or stemming the global HIV/AIDS pandemic, the formulation of our foreign policy must proceed from a solid scientific foundation."[34] If industrialized countries were to leverage national nanotechnology assets into foreign policy, the developed world could ensure that domestic innovation benefits developing countries. In order to promote a global approach for the development of nanotechnology, a portion of public funds from industrialized countries should be marshaled toward areas of research relevant to less industrialized nations. Governments should also consider how to establish incentives for companies to commercialize products and services in the developing world to address local challenges. Nano-diplomacy is arguably one of the most important offerings developed countries can bring to the international table.

NOTES

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