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To excel in physics research in Africa is to conquer Mount Everest without the aid of additional oxygen. In a continent that lacks the infrastructure of research laboratories, technical support, and so forth, relatively few physicists have managed to perform at levels competitive with the best in the world.

Are the challenges of physicists in Africa any different from those facing physicists elsewhere? Physicists everywhere have to convince their governments, businesses, and the public that investment in physics is beneficial and will lead to economic development and an enhanced quality of life. But in countries where physics-based industries are absent and where people are shackled by poverty, physicists face enormous challenges accessing the resources they need. Significant differences exist among the countries of North Africa, the whole of median Africa (sometimes called sub-Saharan Africa excluding South Africa), and South Africa. The level of physics endeavor, which depends on a country's economy, therefore ranges from near world class in South Africa to almost nonexistent in, for example, Somalia.

The physics community is proud of its accomplishments. Physicists can easily identify instances of great intellectual achievement and impact, but unless they have an understanding of the practical value of their knowledge in the contemporary economy of their country, they will fail to persuade investors—public and private—to support them. They also need to understand the rarity of the sequence: Physicists in basic research discover fundamental laws, physicists in applied research then develop concepts, and engineers apply those concepts to produce materials and products that are of value to society. Economic impact generally occurs thanks to the endeavors of teams of physicists and other scientists, engineers, and technical support personnel. Technology often leads science, and basic science is often not the source for new ideas but is used to understand technologies already in use.

Several studies have tried to estimate governments' return on their investment in basic sciences; those studies have produced varied estimates ranging from 0 to 30%.[1] Evidently, it is difficult to demonstrate quantitatively how scientific and technical knowledge and expertise create value in today's economy, probably because the interrelationship between science and economic growth is so complex.

Because many African governments have little confidence in the quantitative value of science, it is hard to convince them to spend their meager resources on physics when large proportions of their populations live on the brink of starvation. A physics culture, however, is crucial for the successful development of technology and the advancement of any society's economy.

Notwithstanding the apparently low return on investment in physics, success stories from Africa should convince other African governments of the economic value such investment might have for the nation. Moreover, as scientists should remind their governments, there are benefits of science that cannot be expressed in dollars.

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Indices of development

How do African countries compare to one another or the rest of the world in terms of physics achievements? Various indicators, including the technology achievement index, assess a country's economic and technological development. The TAI is a composite that reflects how well a country is creating and diffusing technology and how well it is building the human skills base that is so necessary for participation in technological innovations.[2] It measures achievements, not potential or efforts. Because creators and users of new technology, as well as adapters and users of acquired (transferred) technology, need significant physics skills, the TAI can be considered an indicator of the level of sophistication and quality of a country's physics endeavor.

TAI estimates have been reported for 72 countries that have appropriate available data. That so few African countries have TAI estimates indicates that they are technologically underdeveloped or that data are unavailable. Among the 72 countries with TAIs are South Africa (ranked 37th), Tunisia (51st), Egypt (57th), Kenya (68th), and Tanzania (70th). It is not surprising that South Africa and Egypt are among the top-ranked African countries: They are the only African countries that have produced Nobel laureates in science. The 1951 Nobel Prize in Physiology or Medicine went to Max Theiler, who studied science and medicine at the universities of Cape Town and Rhodes. Allan Cormack was a physics graduate from the University of Cape Town and shared the physiology or medicine prize in 1979 for his work on computer tomography. Aaron Klug, a physics graduate of Cape Town and the University of the Witwatersrand, received the chemistry prize in 1982. The 1999 prize in chemistry was awarded to Ahmed Zewail, a chemistry graduate of Alexandria University in Egypt.[3]

Scientific activity is traditionally measured by the production of scientific publications. The world distribution of scientific activity as recorded in 1995 by the Science Citation Index® and CompuMath Citation Index® databases was concentrated in North America, with 38.4%. Sub-Saharan Africa, including South Africa, only accounted for 0.9% of scientific publications.[4] Statistics for research output in physics were comparable: North America contributed

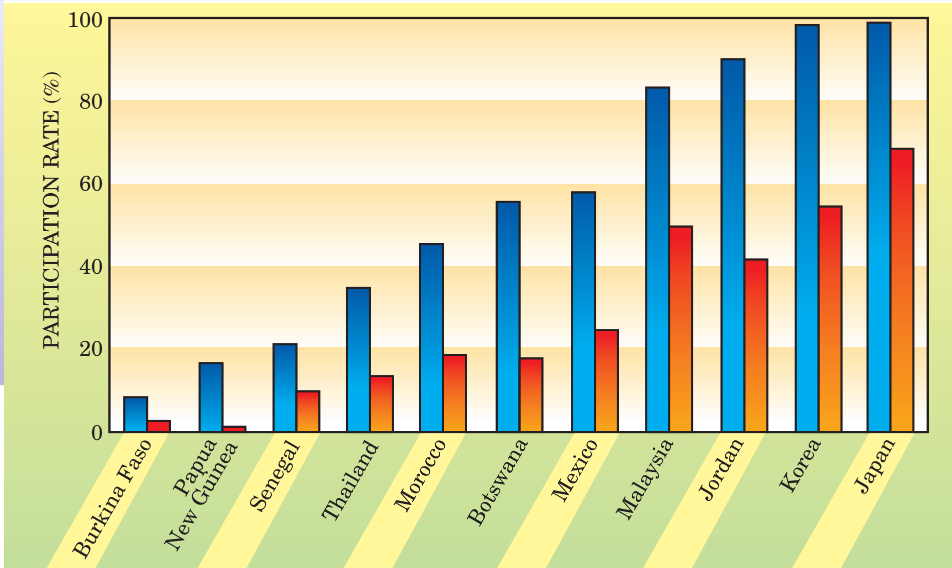

Figure 1. Science education enrollments in lower secondary school (akin to a US middle school; blue bars) and upper secondary school (high school; red bars) vary dramatically across the world. In poorer countries, enrollment can be as low as 5%. Such numbers must be dramatically improved to create the scientific literacy necessary for technological and economic advancement. (Data from ref. 11.)

30.4% of publications in journals recorded in those databases, compared to 0.3% from sub-Saharan Africa.

Scientific citation indices focus on just one aspect of scientific research and ignore research benefits such as technology development and technical expertise. Nonetheless, the unsurprising citation statistics reflect the huge gap in resource development that must be closed if there is any hope of physics in Africa catching up with physics in the rest of the world.

Education and innovation

The participation rate in science education is a key indicator of a country's potential for producing a scientifically literate society, which is a prerequisite for the development of a physics tradition and technological and economic advancement. Secondary-school students in particular acquire skills and competencies most closely related to job-market needs. Osita Ogbu, executive director of the 17-member African Technology Policy Studies Network, put it well: "With knowledge, you create your own wealth, with aid you create dependency."[5]

Figure 1 shows enrollment rates in science at the secondary-school level for a number of different countries. Some of the poorest countries have gross enrollment rates of between 5% and 10%. It is therefore not surprising that the development of a physics tradition, and the corresponding public investment in physics in those countries, is limited, or even nonexistent. With a poor base of indigenous talent to appreciate and use technology, the capacity of a country to innovate, adapt technology to local conditions, and use and maintain technologies is out of reach.

Secondary schools frequently lack suitably trained teachers who are enthusiastic and capable of stimulating scientific thinking. The Kenyan government provides financial support to needy university students, and the poor prospects for job opportunities in the private sector have influenced students to consider a guaranteed career in teaching. Consequently, in 2002, at least 95% of the students who graduated from one Kenyan university with a physics major had completed a second major in education and accepted a government requirement that they teach science at a secondary school after graduation. The scholarship program is a step toward ensuring that science teachers will no longer be a scarce commodity in Kenya. The lack of adequate facilities for science teachers in Africa, though, continues to be a problem.

Catch me if you can

Africa faces distinctive challenges in establishing scientific literacy and technological infrastructures, but the impact of physics on technology is the same in Africa as anywhere else. Still, Africa needs to address the role that physics could play in its technological development. In Asia, several countries, without having an extensive tradition and reputation in basic science, have started to dominate some technological fields. In their experience, practical applied physics goals rather than abstract discipline-specific goals were the most significant drivers of technical innovations for economic growth.

Technological underdevelopment in Africa during the present period of accelerated technological change in the rest of the world makes it literally impossible for Africa to compete internationally, either in manufacturing or in advanced services. Each leap forward in global technology leaves Africa farther behind. Although wealth is not the sole indicator of technological development, it does determine a country's capacity to integrate technology into its economy. In 1960, the per capita income in the richest 5% of countries worldwide was 30 times that in the poorest 5%. By 1997, it was 74 times as high.[6] The period 1989–2000 saw 52 000 additional physics-based enterprises established in the UK. Consequently, 43% of manufacturing employment in the UK is in physics-based industries. Can such development be replicated in an Africa with no technology base?

African countries need to consider whether they should invest in basic sciences—whether they can enter the R&D chain without a solid foundation in basic research. As illustrated in figure 2, science and technology training at universities and research institutes can support industry at various stages. Physics and engineering departments in most African countries would not, on their own, be able to make meaningful contributions to technology development; their research output is just too limited.

Over the years, South Africa's national Council for Industrial and Scientific Research, based in Pretoria, has become a vibrant hub for innovation and technology development. That facility, which undertakes R&D activities for local industries, could serve as a model for other African

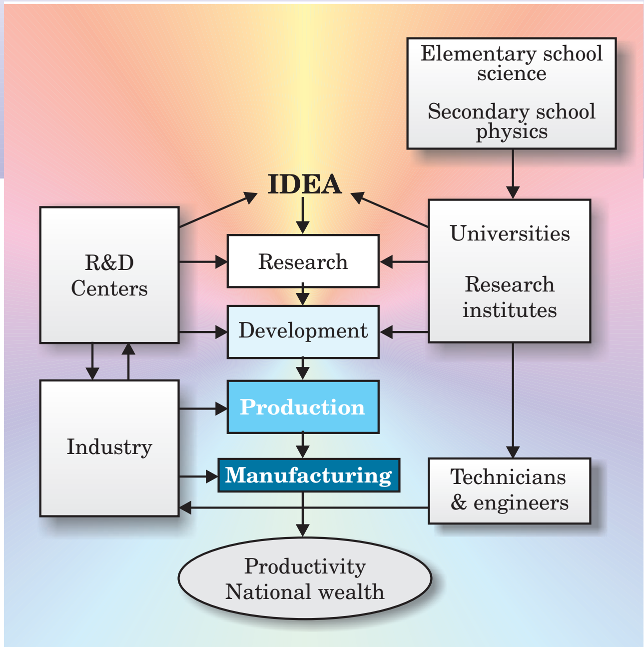

Figure 2. Academic and industrial institutions both contribute to the process that leads to technology development and national wealth.

countries or regions. Even relying on such a model, though, countries that are trying to catch up in the technological, trade, investment, and information environments have little chance of succeeding on their own at present.

In order to compete internationally, African countries must acquire enterprise-specific knowledge, skills, and practices through an incremental process. They must also recognize that networking between competitors is essential in today's economy. The Organisation for Economic Cooperation and Development (OECD), an international collaboration of developed countries, has played an important role in the economic, industrial, and technological development of its member countries. The science and technology initiatives of the New Partnership for Africa's Development[7]—which was established in October 2001 as a program of the African Union—represent the approaches that are necessary if Africa is to catch up with the rest of the world. The NEPAD initiatives should be augmented by north–south partnerships between countries well endowed with resources and those that have few.

Governmental responsibility

Good governance, political stability, and economic development are closely intertwined. African governments must provide the political stability and transparency that are prerequisites for attracting foreign investors. Areas with relatively well managed economies have made comparatively large gains in socioeconomic and industrial development. And with a flourishing economy, most countries will be able to support initiatives in physics that, in turn, will contribute to further economic growth.

What are the future prospects of establishing and guaranteeing a stable environment in which science and technology can thrive? Violent conflict and instability will remain a serious risk for many African countries for the foreseeable future. In 2001, at least 20 countries in Africa were involved in armed conflict or had suffered natural disasters. Those humanitarian crises and complex emergencies disrupted lives and led to the displacement of more than 3 million people. They have also jeopardized industrial and economic development because investors generally seek security and stability.

Promising signs are on the horizon, however. NEPAD's goals are to promote better government, end Africa's wars, and reduce poverty. Once the vision of NEPAD has been translated into action, peace and stability likely will follow, and a major deterrent to investing will be eliminated.

Initiatives in science and technology, however, are not waiting until stability is guaranteed. The first NEPAD workshop on science and technology, held in February 2003, emphasized cooperation and the use of knowledge from institutions of excellence throughout Africa. NEPAD convened a follow-up workshop, the first African Ministerial Conference on Science and Technology for Development, in Johannesburg, South Africa, this past November. That conference launched NEPAD's programs on science and technology.

A clear sign that NEPAD has the potential to positively impact science and technology in Africa is its strategy to network centers of excellence to promote and develop innovations that will address the continent's socioeconomic challenges. The first such network, initiated at the November conference, had been in the planning stages for some time. The African Laser Centre links laser centers in South Africa, Egypt, Tunisia, Senegal, and Ghana. Each partnering government has made a financial commitment to the ALC, a virtual center of excellence that is expected to stimulate innovation, research, and technology development based on laser science.

Although many governments worldwide recognize the need for investment in physics and other disciplines, no universal norm exists for any government to determine the appropriate amount of spending. The OECD countries expend \$200 per inhabitant on R&D; newly industrialized countries spend \$66 per inhabitant; China, \$17; India, \$11; and Africa, \$6 on average.[5] Most countries in Africa—Mali, Uganda, and Zambia, to name a few—spend far less than the average, which means that very few African countries can meaningfully support R&D.

Several declarations by African political leaders have signaled a realization (and commitment on paper) of the importance of science and technology to socioeconomic development. Examples include the Lagos plan of action of 1980, the Kilimanjaro declaration of 1987, the Khartoum declaration of 1988, the Addis Ababa declaration of 1998, and, most recently, the 2003 declaration of NEPAD. The Lagos plan resolved that, by 1990, every African country should be spending at least 1% of its gross domestic product on science and technology.[8] By comparison, the average OECD country spends 2.15% of GDP on R&D and the world average is 1.8%. Finland, with an economy the same size as South Africa, is spending 3.5%. The data suggest that African countries currently commit 0.3% of their GDP, on average, to R&D. Thirteen years after the target date, no African country except South Africa has ever met the goal agreed to in Lagos.

The Lagos and subsequent declarations failed because, without funding from donors, none of the signatories had the financial resources to support those declarations. During the 1970s and 80s, South Africa, because of its apartheid policy, was excluded from participating in

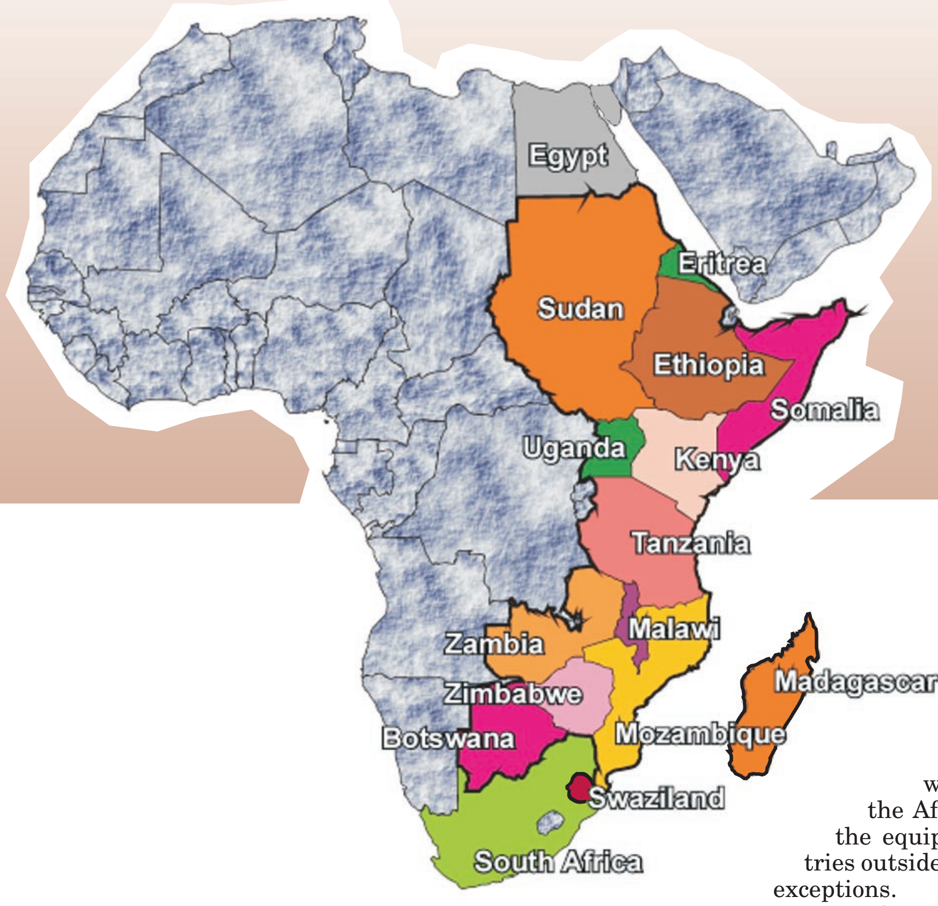

Figure 3. East Africa (outlined in black) stretches north to Sudan, and south to Swaziland. This map includes Egypt and South Africa, which are not considered part of East Africa.

any of the pan-African initiatives, so it was not party to the declarations of 1980, 1987, or 1988. Democracy was established in South Africa in 1994; since then the country has assumed a leading role in the economic, political, and technological development of Africa. The confidence that NEPAD will deliver on its promises is partly based on confidence in South Africa's ability to make a difference.

National missions

To counter international isolation, and to defend an undemocratic regime that immorally imposed apartheid, South Africa pursued key technology missions in energy self-sufficiency and the military during the period 1960–90. Consequently, in 1990, its national R&D spending was as high as 1.1% of GDP. During the period of South Africa's isolation, physics was an attractive option for whites, who had excellent career prospects in the weapons or nuclear technology industries. Once the energy and military programs were abolished, R&D spending dropped. By 1994, it had reached 0.7% of GDP and it has since remained at that level.[9] South Africa has recently released its R&D strategy to double government spending by 2006. The new Kenyan government that took office in 2003 announced it would double the allocation to its National Council for Science and Technology for the year. Although physicists welcomed the increase, it was considered to be inadequate: The council received only about $1.09 million to fund all of Kenyan science.

Many countries in the developed world continue to invest in physics, which they perceive can help enhance the national defense. Their desire to improve war-fighting capabilities through new weapons has not diminished, notwithstanding the end of the cold war and of several regional conflicts. Although Africa has seen endless wars, at times fought with sophisticated weapons, physics in Africa has played no major role in developing those weapons. Most of the weapons used in the African wars, and the skills to maintain the equipment, have been acquired from countries outside Africa. There are, however, at least two exceptions.

During the past 40 years, Egypt and South Africa have been involved in wars in which they used weapons that were developed and manufactured locally. Both countries have a multibillion-dollar weapons manufacturing industry. Egypt's weapons industry is based in companies of the Arab Organization for Industrialization, headquartered in Cairo; South Africa's is based in the Armaments Corp of South Africa in Pretoria. Physics may not play a prominent role in the two industries, in contrast to its prominent role in winning World War II, but the industries could not have flourished without a highly skilled technical workforce that understands physics principles.

Although a defense industry might not be a requisite for the development of physics, it has certainly stimulated a relatively advanced state of physics in Egypt and South Africa, as evidenced by the sophistication of the weapons industry in those two countries. Physics thrives on national programs, but many other industries could equally stimulate physics, with substantial benefits to society rather than the destruction of lives and infrastructure brought about by weapons.

Physics in East Africa

The region of East Africa, shown in figure 3, stretches from Sudan in the north to Swaziland in the south. With a population of 230 million, East Africa includes some of the oldest universities in Africa and some of the youngest democracies. In many ways, the region is representative of the entire continent.

Approximately 140 PhDs participate in active physics research there. That translates into approximately one PhD physicist for every 2 million people. By comparison, South Africa has one PhD physicist per 140 000 people and the US has one PhD physicist for every 8000 people. Of the 80 or so research groups in East Africa, the majority do not

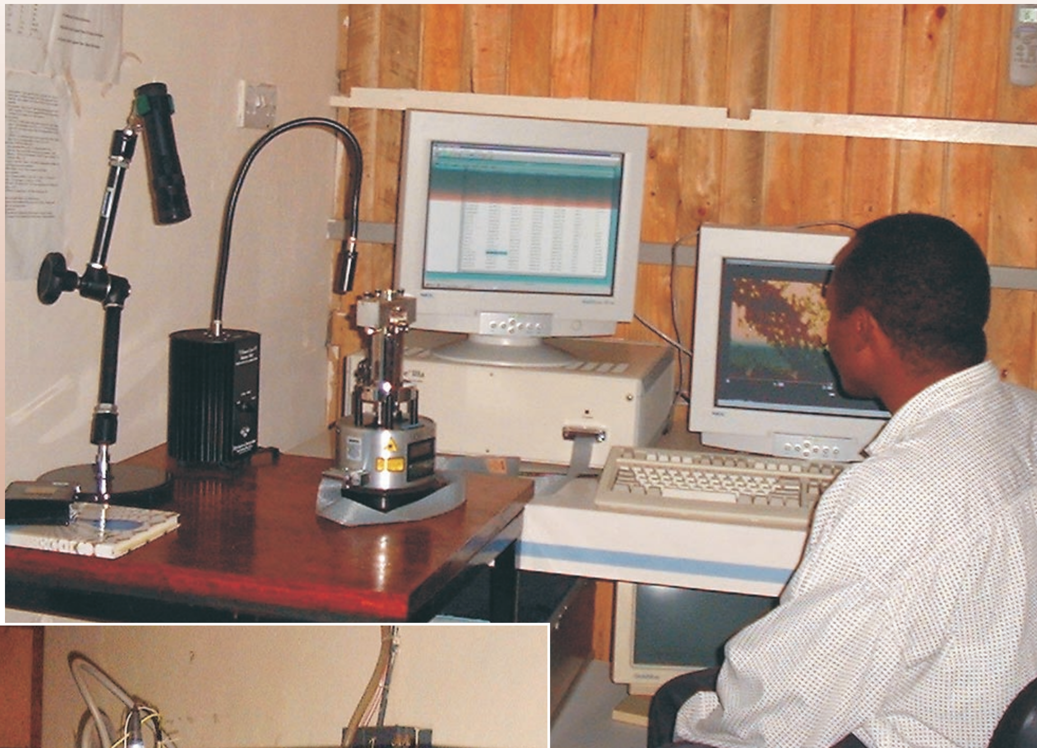

Figure 4. Tanzania's University of Dar Es Salaam boasts a well equipped thin-film physics laboratory. In these two photographs, physics students prepare thin-film specimens with a sputter deposition system (below) and analyze them with an atomic force microscope (right).

have more than one member with a PhD in physics.[10] That might not seem to be unusual when compared with research groups in affluent countries, where one professor manages a team consisting entirely of master's and doctoral students. However, the research environment in the West, unlike that in Africa, is supportive and stimulating, with large numbers of PhD students and postdocs who form the nucleus of research activities.

Most of the physicists practicing their trade in East Africa obtained their PhDs outside Africa, and their research fields have essentially been determined by the opportunities that were provided by the graduate programs in which they participated. Indeed, of the approximately 200 physics articles published by East Africans in international journals during 1993–98, 40% represent work carried out in countries outside the region. One particular international institution that has played an important role in providing resources and opportunities for physicists is the Abdus Salam International Centre for Theoretical Physics in Trieste, Italy. (See the article by Juan G. Roederer in PHYSICS TODAY, September 2001, page 31.) The ICTP provides resources and opportunities so that physicists in Africa may attend classes, perform research, or work on publications at the center for short periods. The ICTP's affiliated centers and visiting scholars programs are well known in African universities; hardly a PhD physicist in East Africa has not had an association with the ICTP.

Many students from East Africa did not return to their countries of birth after completing their graduate studies outside their home country. Estimates show, for example, that there are more Ethiopian physicists practicing their trade in Europe and the US than there are physicists employed in Ethiopia. Moreover, many of those physicists who have returned to their home countries have been unable to procure the resources they need to pursue their research interests or to initiate research relevant to their country. (Nobel laureate Abdus Salam, who returned to his native Pakistan in 1955 from his studies in the UK, had a similar experience.) Consequently, little of the physics research in East Africa relates directly to the continent's technological development. Renewable energy research is an exception, but its story is a cautionary tale.

Most East African countries have research programs in renewable energy. Certain donors, perceiving Africa's energy needs and its many sunny days to be important considerations, have insisted on such programs. However, research in renewable energy has been uncoordinated. Despite 20 years of research programs, 80% of African households are without electricity. Unless an industrial program is created to use the region's physics expertise, renewable energy will continue to be an interesting research topic with little prospect of contributing to economic development. The NEPAD-supported networks in Africa that link centers of excellence have the potential of creating a critical mass of expertise and coordinating and harnessing that expertise to develop useful technology.

Research infrastructures

In East Africa, two programs developing the research infrastructure have been especially noteworthy. During the 1980s and 1990s, the International Program for Physical Sciences in Uppsala, Sweden, invested extensively in the physics department at the University of Dar Es Salaam in Tanzania. The IPPS focused on one particular area of research—thin-film physics—and successfully developed a well-equipped laboratory (see figure 4). The program also provided travel funds so that physicists in neighboring countries could use the Dar Es Salaam facility. Although the facility is isolated in a single institution, it has provided opportunities and resources for a core of the current generation of physicists in the region. The foundation has been laid for the development of physics-based industries in Tanzania, even if the country is not currently in a financial position to develop those industries.

Kenya took a different approach. The Kenyan government entered into a loan agreement with the World Bank and purchased research equipment for each of its five physics departments. Unfortunately, the equipment, which includes magnetron sputtering systems, dynamic mechanical analyzers, and gamma-ray spectrometers, is almost identical for each of those departments. Expertise to operate the equipment is limited and the infrastructure to maintain it has been inadequate. The Kenyan government, however, has made a commendable and serious attempt to cultivate the research base that would eventually support technological development. If Kenya handles its opportunities well, over the next few years its research initiative, combined with its strategy to train large numbers of science teachers, should lead to a flourishing of science in general, and of physics in particular.

Kenya's newly acquired research tools might have been centralized in a single national facility to allow for a wider range of equipment. However, doing so would have introduced traveling challenges. Also, one should not underestimate the impact that a modest research center on a campus might have in terms of stimulating students.

A global village

Scientific advancement cannot occur without quality education; to achieve that quality, Africa will require significant investment at all educational levels. Physics curricula should emphasize project work and problem solving, with a complement of activities in entrepreneurship. One physics department in Kenya allows its students to take an elective course in entrepreneurship offered by the university's business division. That business elective notwithstanding, the physics program at the university is too theoretical and does not produce graduates with adequate practical skills.

Worldwide, competitors have become collaborators and have enhanced their economic, technological, or academic statures by forming alliances and partnerships. For African countries to significantly advance, they must collaborate regionally or internationally. The success of those partnerships will depend on having a well-endowed leading member.

A number of initiatives have recently been launched in Africa to link several countries into groups that develop human resources. In some cases, such partnerships include strong ties with countries in the Northern Hemisphere. Examples include the African Materials Research Society, African Institute for Mathematical Sciences, Working Group on Space Sciences in Africa, and African Laser Centre. Those initiatives, in which South Africa plays a leading role, carry the hope that expertise will be developed to create a science and technology infrastructure in Africa.

Can the world afford to let Africa remain far behind? Without the capabilities and infrastructure to become globally and industrially competitive, Africa has no chance to catch up with the West. The world is willing to spend several billion dollars to verify whether the concept for a particular fusion reactor is feasible. A multibillion-dollar Superconducting Super Collider project was abolished after almost $2 billion had already been spent. Big science consumes enormous amounts of money. Is there a financial benefactor who is willing to fund small science in big Africa?

The world should not give up on Africa. Programs and approaches have demonstrated the potential to develop physics for the benefit of the African society, and having African countries participate with others in a global village of technology is in the interest of every nation.

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