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**From lab bench to store shelves: The benefits of basic research**

*There are two dimensions to basic research. The frontier of science extends all along a line from the newest and most modern [fundamentals]… to the broad and well developed web of [applied] research activities based on fundamentals of past decades."*

This quote from theoretical physicist Victor Weisskopf, a pioneer in quantum physics, highlights the back-and-forth play between different aspects of basic research. In the first stage, the scientific method reveals new insights about nature, which contribute to humanity's general understanding. These insights get printed in new textbooks, and contribute to 'fun facts' in a conversation. The next stage is to figure out how to use this knowledge to benefit humanity. Sometimes the stages aren't clear cut, or transcend scientific boundaries – for example, an early version of the Internet was born while building CERN. Networking computers had nothing to do with the fundamental physics goals of the experiment (detecting fundamental particles by smashing other particles together), but electrical and computer engineers developed the World Wide Web out of the model provided by this physics lab.

Within condensed matter physics, materials science, and engineering fields, grant writers often use direct language to point out how the work will contribute to the solution for a current societal problem or need. These fields have worked together for decades to bring advances in computing, communication, and energy generation – ie, solar cells and smart phones. But the path from laboratory research to device-in-hand is complex, full of incremental success and unseen gains. It usually takes at least 10 years for a new concept to reach maturity and become a marketable product, for both consumer and industrial markets. The research done in this time is still considered basic research, and needs the support of the federal government.

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Prompted by budget cuts and increasing divide between scientists and the public, the National Science Foundation re-vamped the grant application process in 2014, and the review process now places heavier emphasis on the 'broader impact' of proposed projects. Rather than squash fundamental research which would have little societal impact, this initiative gently helps scientists re-frame their research questions in a way to make the already-existent societal benefits more obvious, and to incorporate a dialogue with the public. This is a good step to take for the future, but where would we be today without basic research?

For one thing, cell phones, portable tablets, and solar cells would be very different. All of these are advanced devices which contain a 'transparent conducting electrode', a layer of material which transmits electricity across panes of glass. This material should be transparent enough that sunlight or LED/LCD illumination can still reach the other side of the glass.

The knowledge of transparent conducting electrodes (TCE's) dates back in literature to the early 1960's, yet solar cell panels and capacitive touchscreens were only available for mass-market audiences in the 1980's and mid-2000's, respectively. Thus, there was 20-40 years of basic research, both fundamental and applied, that now shapes how light-based devices are built. What, exactly, though did the basic research consist of?

First, the idea that an electrical conductor could allow light to pass through is surprising considering that most elemental metals are shiny and opaque. Early research in the 1960's focused on characterizing the optical and electrical properties of thin metallic films. These films were not elemental metals, and were combined with oxygen to form unique crystal arrangements. Oxide films are usually fairly transparent, and thus a metal-oxide film turned out to have some properties of both of its constituent parts. This strategy helped build an understanding of how a material could be both conducting and transparent. An early commercial use of a TCE was with solar-powered calculator using a thin-film solar cell.

The next wave of research into TCE's focused on how different substrates, or the material onto which the metal oxide is deposited, affects the film quality. Solar cell materials can be very sensitive to exact material specifications, and certain deposition methods rendered material alloys that degraded device performance. Furthermore, solar cells are made from a wide range of materials, and what is good for one type of solar cell may not work for another. The time and research money spent characterizing deposition methods was the most important for bringing these materials to market, and solar cells started making their mark in the early 1990's, although they were still fairly inefficient.

By the early 2000's, film adhesion, parameters controlling electrical conductivity and optical transparency (a source of loss for solar cell energy), and the response of the material to physical stress had all been heavily investigated for a wide range of substrates. Patents for capacitive touchscreens using metal oxides started to increase, and big technology companies start introducing hand-held products with touchscreens. The high-profile Apple iPhone, launched in 2007, showcased the modern capacitive touchscreen using an indium-tin-oxide (ITO) conductive layer. Meanwhile, solar cells reached at least 40% efficiency in lab-based devices, and total worldwide power generation passes 1,000 megawatts. Most approaches to solar cell technology had incorporated a transparent conducting layer.

The benefits of 40 years of research into TCE's extend beyond products available at the consumer level. Because of the solid understanding of the material and relative ease of use, ITO has become a standard material to aid groundbreaking opto-electronics research. Understanding why a metal oxide can be a good conductor has led to tailored electronic properties in new materials. ITO has been used as a platform to study outstanding questions in light-matter interactions, and recent characterization of an as-yet un-measured optical coefficient (the nonlinear susceptibility) showed a surprisingly large value - a result which highlights the fact that ITO is not about to fade into obscurity. Meanwhile, transparent conducting electrodes like ITO are so ubiquitous that hobbyists can purchase off-the-shelf conductive glass to advance their own creations.

Every field of research, from high-energy physics and materials science to medicine and microbiology, has their own stories of unexpected scientific and societal gains from fundamental research. What's more, the solutions to fundamental research problems may take decades to solve, like vaccines and gravitational wave detection. Having a strong commitment to foster research at all levels is necessary for the advancement of the human race.

- References

1. Modified Quote from Weiskopff, from P. Anderson's More is Different.
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2. NSF Broader Impacts,