Energy Breakthroughs and Education

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As I have learned from the lessons of history and through my years on earth, the quality of life and the statistical chances for human survival are determined primarily by **access to energy**. However, as an educator, I have learned that the quality of life and the statistical chances for human survival are determined primarily by **access to education**. I still remember the day that as Headmaster of the Spence School in NYC in the early 1970s when I realized the relationships and the connection between **education** and **energy** as I wrote a very simple equation on my blackboard clarifying the relationship between the two.

This was my personal epiphany, my Einstein energy moment, my equivalent to his famous $E=MC^2$ equation where he recognized that energy and matter were interchangeable forms of the same quality. Though compared to Einstein my modest insight was trivial, I was so stunned by the importance of energy to education and what this insight might mean to education that I slipped out of my office on East 91st Street and walked down 5th Avenue next to Central Park in a daze trying to digest the implications of this new understanding. Before the day was over I was so engrossed in coming to terms with these new thoughts that I walked all the way down past Wall Street to Battery Park at the southern tip of Manhattan and somehow returned to my home in the Upper East Side at dusk without any memory of my saga. What I suddenly had realized was:

- The problem facing education is not a lack of knowledge, commitment, zeal, capital, programs or reforms; but a **lack of available energy, an energy shortfall**. Unlike many other delivery systems that have harnessed technologies to aid their workers, education still relies primarily on the manual labor of teachers. The system needs more available energy to provide the work required to insure the best possible educational outcome for each child.
- This critical work component cannot be realized by adding additional human capital (teachers and administrators) because systemic improvement will only

come when the amount of available work soars beyond what is humanly possible in the current system.

- This additional energy/work component can be realized only through introducing technologies to support the manual efforts of the teachers, students, and parents, both at home and in school. Teachers have reached their natural work limits.
- A new technology is evolving that is ideal for this task (the microcomputer). One of the co-founders of Intel who developed the first microcomputer in 1971, Gordon Moore, had calculated that its capabilities would continue to double every two years until at least 1990. Shortly before my defining moment I had read an article by Moore, and I realize now in fact that he was right.
- The computer is the final critical component which allows technology to teach children individually, interactively, and with stunning artistic effect. This is the only technology that can act as a teacher. All other technologies such as radio, TV, movies, videotapes, books, etc. lack sufficient artificial intelligence to change the instructional sequence based on student responses to the materials. In addition, they keep the learner passive and force him or her to follow an inexorable learning sequence that may or may not be appropriate to individual needs. Finally, ass Moore's law indicates, the computers' capabilities are in their infancy and will continue to improve in the future.
- The cost benefits are compelling. As predicted by Moore, computers have improved in speed, storage, and functionality at 1% a week (doubling about every two years) for over 40 years without additional cost to users. Any trend that provides twice as much for nothing every two years is destined to have an extraordinary impact, particularly if the trend is likely to continue for the foreseeable future and can improve the productivity of workers in a myriad of organizations. Each doubling provides significantly greater functionality. In 2008 the doubling provided an additional half a billion transistors on a chip the size of a fingernail for engineers to work with, and in 2010 they will have another billion at their disposal. Not bad considering the first microcomputer in 1971 used only 2300 transistors.

- Perhaps my most stunning realization that day was that the entire educational delivery system (including my efforts at Spence) was wedded to an approach that **could not be significantly improved no matter how well the teachers perform or how much money is spent on the mature delivery system because it relies on manual labor as its primary source of energy and work.** I also realized **that almost no one recognized that this limit would have to be circumvented before significant progress could be made.** We have lived in the current manual educational delivery system for so many centuries that it has never occurred to us that, as in the case of all delivery systems, the introduction of new technologies would profoundly impact how much work each teacher could accomplish for the children. All current and previous planning assumes that the teacher is the primary source of work for the delivery system.
- What I also realized that day was that, as humans, we organize ourselves into **delivery systems** to deliver goods and services to society, but delivery systems are limited by the amount of energy that is available to produce the useful work in the system. **All useful work is generated initially by humans, but over time they find new sources of energy to add to their ability to deliver work manually.** The **transportation delivery system** harnessed wind for sailing, horses for travel on land, and then added railroads, steamships, bicycles, cars, trucks, balloons, trolleys, buses, aircraft, and rockets to circumvent the limits of manual labor in transporting people, goods, or services.

  Think of the improvement in the **communications delivery system** the day Americans completed the telegraph link between the East and West coast that delivered information over 40 million times faster than a human on a horse (The Pony Express). The result was the collapse of the Pony Express business within a few days.
- Finally I realized that I was forever sensitized to a **new metric** to evaluate the potential of any educational approach: I now start my analysis by checking how much work is available in the school system under discussion because this sets the potential parameters for the success of the system. Unfortunately this summarily dismisses the importance of almost every educational reform currently being used

or introduced because unless the reform involves introducing new technologies carrying the latest software, then I know that although it may have limited local value under an outstanding leader, that it ultimately is not scalable throughout the educational delivery system.

Unfortunately a great leader can harness just enough work in a local reform effort to be successful because there is just enough manual work available in the system **if it is organized perfectly**. I say "unfortunately" because the little flashes of hope from the occasional successes of manual efforts blinds the educational delivery system to the underlying problem and leaves the leaders perpetually scrambling to find a new reform because the necessary limits of the current manual system are frustrating to them.

- Also unfortunately this insight has left me a boring pariah among my colleagues because after a routine survey of the approach they are extolling, I dismiss their latest visions of reform after failing to convince them about the limits of their approach, much as a military man would when his colleagues want to discuss the deployment of the cavalry when he knows aircraft and tanks have been invented and are available.

However that day I was suffused with a sense of hope for education as I realized not only would my students at one of the elite schools benefit from technology, but also more importantly, all students no matter their economic status or location could also be given access to the finest education imaginable. When services are delivered manually, only those with capital, political power, or extraordinary talents can gain access to the best, but when services are delivered by technology, all can receive the identical benefit. In the jargon of education, technology has the advantage of being **scalable,** and scalable means the instruction can be duplicated rapidly, accurately, and inexpensively. Radio and television are scalable: using the speed of light, programs can be sent throughout the globe in seconds and each recipient receives an identical presentation. Technology- based education is scalable and with the help of the computer can provide interactivity which allows totally individualized instruction for all children at any time or place.

My predictions for technology, based on my insights that day, were actually a bit tame, for they did not take into account the invention of the Internet with its capability to link these powerful computers and provide near universal access for workers, families and institutions anytime anyplace. These two technologies (the computer and the Internet) in combination will provide the necessary energy/work component for the desired improvement in the educational delivery system that manual human labor alone cannot provide.

While it is true that technology in the form of books contains stored work from others to aid in the educational process, books cannot actively teach a student. In fact the student must wrest the information from a static book format in order to benefit from the information. Students or teachers must do all the work and provide the instructional context and understanding from the book's passively stored information. Computers add intelligence to the process that provides interactive individualized instruction for each child that can change the instructional sequence to fit the student's current level of understanding. Ultimately the presence of the Internet will allow such curriculum to be available anytime anywhere for any child.

As I pondered these insights, I realized that once a new source of energy was available for a delivery system, no other improvement could offer a fraction of its impact. More importantly, those responsible for the leadership of the delivery system should make the introduction of the new energy sources their highest priority. I also realized that once a delivery system matures and uses its resources reasonably well (as American education has), spending more money on improving it is generally fails because most of the obvious inefficiencies have been addressed as the organization has matured.

In most successful countries the educational delivery system has evolved into a generic model (**the standard model**) and matured after trying many approaches where the federal government, state legislatures, and local entities provide taxes for public school districts that are overseen by a local board. There are also state boards of education and regents that help set policy. There is usually district testing, state testing, and federal testing. The governors and mayors also have a vested political interest in the educational system and frequently make it a high political priority for their administrations. Most countries districts and states require certification for teachers who are drawn from schools of education that require a formal structured curriculum for their education majors. Many countries and states are also unionized with formal pay scales.

Trying to find a new way to improve this mature formalized delivery system is not likely to be successful because over the centuries almost every conceivable option has been tried. Most reforms either try to add more people to the system or try to use the available work in the system more efficiently. Neither of these approaches has succeeded in improving the system as a whole no matter how much money is added to the school budgets. The costs to generate even a slight improvement become prohibitive; nevertheless, desperately desiring improvement, taxpayers, legislatures, and the business community keep raising budgets and adding personnel without seeing any substantive improvement.

The solution is to introduce a new affordable source of energy to support the workers rather than spending infinitely more capital with diminishing returns trying to improve the efficiency of the manual workers, and/or to keep hiring more of them. In other words, the teachers need the work bonus that technologies can provide to help them succeed in their work.

Spending billions on the Pony Express to improve it would not have added much to what was basically a one horsepower energy model (by definition a horse is capable of accomplishing one horsepower of work). This is a critical distinction to understand. The output of any delivery system is determined by the amount of work its components can generate when it has reached reasonable efficiency. When more work is desired, the use of technology is generally preferable to adding more human manual labor because it costs less, makes better use of time, and exponentiates the amount of energy and work available for the delivery system.

These insights transfixed me and left me talking to myself and jostling crowds of people on my unplanned intellectual safari. What I realized was that the centuries-old educational delivery system is primarily a manual one where teachers are responsible for most of the work. Aside from the technology of books which represent a useful and inexpensive source of stored work, teachers are given very little technical support and are limited by the amount of useful work they can accomplish through their physical and mental efforts in a six-hour school day encompassing slightly less than half the days in a calendar year. I recognized that any reforms that had been introduced to improve the system were only “**efficiency reforms”** that attempted to use the available work in the system more **efficiently** rather than offer new technological breakthroughs to add more work to support the teacher’s manual efforts. Thus while other delivery systems such as communications, agriculture, the military, transportation, and construction had used the benefits of an extraordinary array of ever improving technologies that had flooded the system, schools had not.

Finally, I saw with devastating clarity that since the educational delivery system is not adding more work to the system beyond piling in specialists, administrators, and paraprofessionals, the reforms will not succeed. Since the core problem is a scarcity of work to individualize instruction for the children, only the introduction of more energy and work through the use of technology and excellent software can provide a solution.

For over 35 years since that personal epiphany, I have studied and articulated this issue. Once I understood the implications of energy and education, I resigned from Spence and formed a nonprofit institute (the Waterford Institute) to develop the software for the coming educational revolution. Along the way the Waterford Institute started a research school, The Waterford School, to test its concepts and build models to help public schools as well as to facilitate the Institute’s research in the development of software. Today, that school is located on 45 acres in Sandy, Utah, a suburb of Salt Lake City, has over 1,000 students from preschool to high school and has the highest scores in the state.

I often reflect on the day I made my unusual discovery about education and energy and understood that almost unnoticed a new source of energy for education was available that would revolutionize our ability to offer children both equity and excellence in their education. We know from our experience with atomic energy, there can be dangers associated with introducing new sources of energy into human affairs. However, this paper will concentrate on the positive potential the new energy sources will offer all children in their educational quests. I will describe and clarify what I have learned from my own journey as well as from the work of others about this coming educational saga. My hope is the reader will not only be edified, but also excited, hopeful, and willing to become an active participant and supporter of this coming educational revolution.

A History of Some Energy Epochs

The Fertile Crescent Package

From the dawn of civilization the need for food energy required humans to become hunter-gatherers who constantly moved as they foraged for food sources which were seasonal in nature. But after the last ice age began to recede about 13,000 years ago, innovative humans transitioned from being hunter-gathers to farmers by learning to grow food crops and domesticate animals. Of the over 200,000 wild plants that existed, they found a group of cereals (wheat and barley) and pulses (peas, beans, lentils) in the area of Southwestern Asia called the **Fertile Crescent** (Iran, Iraq, Syria, Jordan, Turkey, Egypt). These large seeds contained significant nutritional energy that was cultivatable and storable. Similarly they discovered from a potential worldwide pool of about 150 large animals that 14 were capable of domestication. Of these the Fertile Crescent had 4 that provided additional food energy (sheep, goat, pig, and cow).

Once access to the storable and relatively portable energy of plants and animals was available, people were able to give up a nomadic life, form cities, governments, centers of learning, and armies. Freed from the need to travel in order to survive, they now had time to develop other sources of usable and storable energy in the centuries ahead.

As Jared Diamond notes in his perceptive survey of human history, *Guns, Germs, And Steel*, following the last ice age the knowledge and use of the products of this **Fertile Crescent Package** took thousands of years to spread west to England and East to Japan through all 8,000 miles of Eurasia. With this knowledge, the husbanding of animals and the cultivation of crops became the center of food energy formation, and the world went from having no farmers 11,000 years ago to mostly farmers 8,000 years ago.

Energy from Animals, Wind, Water, and Fire

In addition to using the food energy from the **animals**, humans learned how to harness their physical energy to help them with their **agricultural and transportation needs**. Those with access to the most storable and portable food energy became dominant on the globe. Where this food energy was available, people now had time in the centuries that followed to experiment with other sources of energy and to develop technologies to help them. For example, they harnessed natural forces such as wind by inventing sails to capture the **wind's energy** and ships to carry goods and people throughout the world over the canals, rivers, lakes, seas, and oceans that opened up about 70 percent of the earth's surface to liquid low friction travel that was barrier free. Water-based transportation costs about a 20^{th} of land-based. The economies of water-transportation allowed people to travel more easily, to expand trade and commerce, to extend their military interests, and to explore the world and find additional sources of energy both in foreign lands and from the fish in the oceans.

They also developed **windmills** to help them grind the seeds of plants to make flour and cornmeal, and they turned to **running water** as an alternate source of energy for their mills to replace horses. As miraculous as these energy sources were, water and wind have the liability of not always being available since the wind sometimes stopped blowing and the numbers of usable rivers were limited and sometimes dried up during droughts.

The great source of consistent energy that accelerated the amount of available energy and launched the industrial revolution was the taming of **fire**, a phenomenon that has always coexisted with man's presence. Fire can be generated by random strikes from lightning, and about 8,000,000 lightening strikes a day hit the earth. Fire also occurs from lava flow during certain types of volcanic eruptions. We do not know how humans learned to ignite fire with friction from striking flints or twirling sticks, but gradually they developed the capability to have access to it on demand. Fire is like a wildcard for humans that is so powerful, mysterious, and helpful that myths (Prometheus) depict it as being stolen from the gods. The taming of this remarkable energy source, unlike anything else familiar to humans, is one of the great themes in the history of civilization.

The hallmark of **fire** is that it is a chemical reaction that generates the **release of energy** in two forms: **heat** and **light**. The process is initiated when **fuel**, **oxygen**, and **heat** are combined. Typically the fuel is wood, coal, gas, oil, etc., the oxygen is available as a gas in the air, and the heat must be sufficient to ignite the fuel (for example wood needs a temperature of 617 degrees Fahrenheit to ignite). The energy from combustion is so dramatic, and at times dangerous, that people have organized strategies and resources to produce and control it (fireplaces, stoves, chimneys, bellows, matches, lamps, candles, firehouses, firemen, etc.). At first fire was used mostly for heat, cooking, and clearing land, but gradually people learned how to use its energy to crack open and manipulate many forms of matter and discover the basic elements. For example the use of fire helped humans distill and utilize metals to produce tools. Alchemists and curious innovators used the energy from fire to produce various chemical compounds and elements which helped to initiate the science of chemistry and physics.

The Early Educational Technologies

The technologies of writing, drawing, and painting became the most useful early inventions for education. They allowed ideas, concepts, literature, scripture, music, art, science, and mathematics to be stored so others can have access to it long after the creating event. As the linguist Steven Pinker notes, speech is quite a miracle as people can move their lips and tongue and take control of other peoples' minds through the spoken word; however, access is limited to those that are within the range of hearing at that moment or hear it spoken to them by someone who was there or has heard about it.

But once the work is stored then it can be available to people in different epochs and lands. The most significant early educational technologies were writing instruments made of chipped stones, styluses, pens made of animal quills, chalk, ink, etc. or the storage media such as skins, cave walls, stones, bones, clay, wax covered tablets, papyrus, canvas, cloth, paper, etc.

The real breakthrough came in the 1400s when the printing press was invented which allowed books to be scaled inexpensively with minimum human labor required for each accurate copy. As a Chaucer scholar I was interested to discover that we do not have Chaucer's original manuscripts, and that as each copy was made manually (literally), errors were made which became a new template to which new errors were added as it was copied by someone else. Here is a clear case of the power of technology to scale accurately without introducing a cascade of errors with each copy.

We are fortunate to have the ability to scale words and pictures accurately through books, but we have not learned to scale the ideas and concepts the teachers are passing on as they lecture and interact with their students. Only technology can scale the interactivity of teaching with any accuracy. Currently when we try to initiate new reforms, they are taught by trainers who manually train other trainers who in turn train others. Unfortunately, each worker only teaches part of the concepts accurately and frequently adds examples and biases that slowly dilute the accuracy of the intent of the original author.

Another interesting fact about the use of technology is the ambivalence that humans have about using it. For example many people criticize the use of computers for children because they isolate themselves and work on something mechanical instead of working with people and other humans. This is the same criticism that people leveled at the use of the book in the 1400s. And even Plato’s dialogues written more than 1800 years before the printing press was invented have some harsh things to say about an earlier technology (written manuscripts). They disapproved of the danger in having manuscripts available for students to learn from instead of memorizing their lessons from the oral speech of their tutors. Obviously students become lazy and their minds flabby when they no longer were forced to memorize the spoken word.

The Industrial Revolution

During the 1700s the harnessing of fire to drive machines launched the industrial revolution. By 1712 Thomas Newcomen developed the first commercially available steam engine that reached as much as 15 horsepower, but the real revolution started between 1765 and 1785 when James Watt developed a more efficient steam engine that had four times the power as Newcomen’s while using only one-third of the fuel (coal). The steam engine helped to pump water from coal mines, provided power for textile factories, and aided in the smelting of iron. Because Great Britain was the first nation to harness this new source of energy commercially, it benefited to an extraordinary degree compared to other countries.

The Economic Implications of Energy

In reviewing the history of economic growth, Jack Goldstone concludes that Great Britain’s experience was unique in that it was the first to create “self-sustaining growth after 1830.” Unlike other nations whose economy would flower for a period and then falter, Great Britain created an "engine science" that led to the "creation of engines specifically designed to convert fossil fuel energy to useful work" (*Efflorescences and Economic Growth in World History*). He notes that England benefited because it "became grounded in a new scientific knowledge that produced . . . undreamed of sources of energy," and that "It is difficult to overstate the advantage given to the first economy or military/political power to devise a means to extract useful work from the energy in fossil fuels." In his book manuscript, "*THE HAPPY CHANCE: The Rise of the West in Global Context, 1500-1850,*" Goldstone writes:

> The crucial watershed in the history of the West, indeed in the history of the world, occurs relatively late, in the late eighteenth and early nineteenth centuries, with the widespread harnessing of fossil-fuel power to economic activity through a wholly new mechanism, the steam engine. . . .By providing a way for the first time in the history of mankind to turn heat energy into motion for work, for manufacturing, for transportation, for construction, and indeed for revolutionary activities throughout the economy, [we reached] the real and the *only* true watershed between the modern industrial world and our preindustrial past.

But mines, mills, and factories lack portability. What was needed were more **portable energy sources** to give more people access to energy. Shortly after 1800 the steam engine developed the necessary portability and was successfully used on ships and trains.

Electricity: Dynamos and Motors

While steam development was maturing, a stunning new energy source called **electricity** was developed beginning in the 1820s with the research of Michael Faraday at the newly formed Royal Institution in London. William Hyde Wollaston called Humphrey Davy's and Faraday's attention to some interesting concepts in electricity, and Faraday conducted some critical experiments which led to the discovery of the electric motor in the early 1820s, and then ten years later, he worked out the concepts behind the dynamo, a device to generate electrical current. Faraday's work was formalized mathematically a few decades later by James Clerk Maxwell whose four equations laid the groundwork for the electrical industry by quantifying the electromagnetic force for human use.

The electromagnetic force is one of the four basic forces that control the energy of the universe, and because of Faraday's and Maxwell's research, the development of **electricity** was possible now because it could be produced with dynamos, used in machines with electric motors, and by the l880's transmitted over power lines to factories and homes. Using electricity, the telegraph was developed in the 1840s and by the 1860s linked the United States from coast to coast. The telegraph was followed by the telephone, and then by the early 1900s Marconi discovered how to make electrical communications wireless, and electromagnetic waves could be transmitted at the speed of light without wires throughout the globe. From this followed radio and television.

Photography

The speed of light in the form of photons is used by humans to see the world directly through their eyes which collect the energy of the photons as they reflect off of physical objects. The visual images help them comprehend their world and universe. Humans invented telescopes and microscopes in the 16th and 17th centuries to extend their visual abilities, but all through history anything they viewed remained transient until they invented processes using technology to store their visual images on cave walls, rocks, bones, animal hides, papyrus, paper, and metals. Unfortunately each visual image had to be hand made and was not replicable and scalable. The invention of the printing press in the 15th century helped break the manual barrier by allowing print and images to be replicated and scaled inexpensively. Still, each image had to be hand made by specialists before it could be replicated.

Scientists worked on democratizing the ability to have accurate images available. William Hyde Wollaston developed a device in 1807 called the **camera lucida** which reflected a scene through a prism down onto a flat surface with a piece of paper where a person viewing the scene by looking down through the prism could copy it accurately. This was helpful to a degree, but the eventual invention of the photographic process in the 1830s and 1840s made two dramatic changes:

(1) It freed the hands and democratized the image making process, thus allowing those without artistic skill to produce accurate images.

(2) It exponentiated the amount of available energy by having the photon and its energy interact directly with chemical compounds that are altered to produce a scene identical to the one being focused on by a lens. This happens almost instantaneously and relieves the human of having to sketch or paint every detail.

By harnessing the energy of the photons in combination with various chemical compounds to produce the picture instead of just imprinting a temporary image on the brain, many benefits followed. First, there was now an inexpensive record available; second, the record was accurate and did not depend on manual skills and significant time commitments to produce; and third, the images were able to be scaled accurately and inexpensively either through making additional copies from a negative or by using the printing press and publishing them in magazines, newspapers, journals, or books.

William Henry Fox Talbot who produced the photographic process that allowed us to make negatives and copy the prints published the first photographic book in 1844, *The Pencil of Nature.* The title is significant because it is the best description he could offer reflecting his awe of this new energy source where the work was being accomplished by energy from nature, not man. The implications are stunning because when nature wields the pencil, every leaf and twig in a huge tree can be captured instantly without additional work from the human taking the picture. Michael Faraday, a friend of Talbot, and a great scientist at the Royal Institution who was instrumental in taming electricity, wrote of similar sentiments after viewing Talbot's work:

> No human hand has hitherto traced such lines as these drawings employ. And what man may hereafter do, now that Dame Nature has become his drawing mistress it is impossible to predict.

Each generation of inventors, scientists and businessmen has developed new products that come closer to using the full potential of the speed of light in photography while reducing the energy and work required by humans to produce usable photographic images. Currently the digital revolution in photography is changing the photographic industry as sensitive electronic chips are replacing film as the collectors of the energy of the photons. Overnight, film processing and darkrooms are disappearing. And since the chips are following the curve of Moore's Law, the cameras are improving in storage and power at 1% a week without additional cost. Using satellites, digital cameras, microcomputers and the Internet a photographer can take a color photograph, download it wirelessly to his laptop, send it up to a satellite, and have it to his newsroom editor within a few moments.

A similar revolution has taken place in the film industry which started when still pictures were run in sequence to produce motion pictures that are rapidly scalable to theatres and homes, both in film and television formats. Suddenly people were given access to great drama without having to travel to a live show at great expense at a fixed time. Now they can see them at home on television or on rented DVDs at their own convenience any time of day or night, while still retaining the ability to go out to see a movie at a convenient time at a local theater.

The Internal Combustion Engine

During the late 19th and early 20th centuries the steam engine was gradually replaced by the internal combustion engine which used gas and oil as its energy source. The new engines had an advantage because they moved the fire combustion into the engine cylinders (thus the phrase **internal combustion**) unlike the steam engine that was most efficient when the combustion chamber was external to the cylinder. This improved the power and portability of the engines and led to the development of motorcycles, cars, trucks, airplanes and a host of small portable engines that could be used for everything from lawn mowers and chainsaws to model airplanes and portable generators.

Henry Adams and his Prediction of Infinite Energy Sources by 2000

About the same time in the latter part of the 19th century a great historian, Henry Adams, began to track the rapidly increasing access to energy that individuals were deriving through these new technologies. Accompanied by a knowledgeable physicist, Samuel Langley, Adams was stunned by the exhibits of the emerging energy sources such as the internal combustion engines and forty-foot dynamos at the Paris Exposition of 1900 designed to generate electricity to run electric motors and provide light. Using his scholarly skills, Adams tracked the production of coal back to the early 1800s and discovered that the used of coal energy had been doubling every ten years as it was used to fuel energy for steam engines and dynamos. He also calculated how much horse power was available to the average person in the early 1800s as contrasted with the early 1900s. He found it had evolved from a few horsepower to thousands of horsepower in the form of engines driving trains, ships, and factories. Extending the trajectory of the increasing energy curve forward, he calculated that by the year 2000 people would have access to unlimited energy. The prediction both amazed and frightened him.

Atomic Energy

Adams' predictions have come true as scientists have continued to develop new and more efficient energy sources. The 1940s produced three remarkable breakthroughs. **First**, a second basic force of nature, **the strong nuclear force**, was utilized in the form of **Atomic Energy,** which, as Adams predicted, was both hopeful and terrifying. Tapping the strong nuclear force has the advantage of producing the maximum theoretical energy available in matter because it transforms matter into pure energy following Einstein's famous equation that suggests that energy and matter are different states of the same thing ($E=MC^2$). What was startling was the discovery that transforming just a little matter into pure energy releases an unbelievable amount of energy. Although we still have much to learn about atomic energy and the strong nuclear force, having this new source of powerful energy available suggests that humans may transition to using it as fossil fuels are used up. The fusing of our simplest element, hydrogen, through the force of gravity (another of the four basic forces) unleashes the strong nuclear force found in our sun and all other stars. The sun provides all of earth's energy except when our scientists work with the strong nuclear force provided by atomic energy.

The Transistor: 30 Tons to a Few Ounces

A second scientific breakthrough in the 1940s was the **transistor** which was developed at Bell Labs. Transistors were used to replace most vacuum tubes because a transistor takes little space and current compared to a vacuum tube. The first powerful electronic computer, ENIAC, built in 1946 used about 18,000 vacuum tubes, weighed 30 tons, and required so much current that it temporarily dimmed the lights in its neighborhood when it was turned on. The difference between the transistor and the vacuum tube can be readily understood by comparing the characteristics of the first transistor microprocessor (the 4004) built by Intel twenty-five years later in 1971 which had about the same power as the ENIAC but required only 2300 transistors which were stored on a **tiny chip 1/8th of an inch wide and 1/6th of an inch long.** The small computer chip, which used a new process that allowed many transistors weighing a few ounces to be placed on a tiny area of silicon, was now equal to a computer that weighed 30 tons, and its remarkable capabilities started the microprocessor revolution.

An important characteristic of transistors is that they are similar to money in that they can be utilized or expended for many purposes. Transistors can be used as capacitors, resistors, amplifiers, gates, etc. and as such can provide the components to build radios, TVs, telephones, computers, memory, etc. Their small size and low current drain make them ideal for developing complex electronic circuits.

Moore's Law

Another advantage of transistors is that they are capable of being fabricated in less and less space on a silicon chip, with each new design generation doubling the number of transistors available every two years at the same cost. Engineers call this Moore's Law, which suggests that since 1965 the number of transistors that can be formatted on a silicon chip has doubled every two years. Another way to state this astonishing law is to note that computers using transistors have been improving since 1971 at one percent a week in power and storage with no additional cost. The doubling phenomenon seems impressive at first, but over time it becomes formidable in its implications. Early in the doubling cycle in the late1960s the number of transistors was in the tens and hundreds, but by 2006 the continuous doubling every two years provided engineers with an extra quarter of a billion transistors at no additional cost, and by 2010 they will be designing devices with an extra billion available. Recall that the first microcomputer with 2300 transistors 1/8th by 1/6th of an inch in size duplicated the power of a 30 ton machine built 25 years earlier with about 18,000 vacuum tubes, and then try to envision the implications of having the energy of a few billion transistors available on a small chip.

The doubling phenomenon is strikingly powerful over time. As the economist Paul Romer has noted, if a penny is placed on the first square of a checkers or chess board and then doubled on each space until all of the squares have been used, the doubling takes place 63 times. By then the penny will have expanded to about 92 million billion dollars.

The transistors developed on integrated circuits have only doubled 21 times to date as compared to the chess board which provides 63 possible doublings. Engineers suggest that there are at least 4 more possible (from 2008) over the next 10 years before the transistors become packed too densely to allow more doubling. The silicon transistor limit will not stop the future progression of new energy sources, however, because new scientific breakthroughs will introduce new technologies that will run through equivalent doubling sequences. The great challenge of the future will be our ability to understand the potential of these resources and to utilize them wisely and well. They **will** exist.

The Computer: The Third Breakthrough in the 1940s

In addition to the unleashing of atomic energy and the discovery of the transistor, the 1940s saw the invention of the computer. The reader should understand that in addition to unleashing ever increasing power and storage as Moore's law plays out, there are some other underlying advantages that the computer brings. For one thing, a computer speeds up the number of useful work cycles that can be achieved in a given time increment. In order to utilize energy to produce useful work, a **useful work cycle** has to transpire which follows a **programmed sequence** that takes **time**. Humans tend not to notice the program element required to use their energy successfully. For example for thousands of years we have fussed with food preparation for every type of plant, animal, vegetable, fruit, nut etc. that we could find. Gradually we worked out formal programs which if followed in a carefully delineated work sequence produce appealing dishes. We have invented the word "recipe" to describe the program that should be followed, but we do not think of it as a program, just as a recipe.

But we are sensitive to the time it takes us to complete the work cycle, and when possible we speed it up by using technologies such as a microwave oven. **The computer offers one of the greatest breakthroughs in the history of energy development**

because it is designed to speed up useful work cycles. In fact the first successful electronic computer was constructed in 1946 to speed up the specific work cycle required to calculate the trajectory of artillery shells which involves a very laborious manual process. The calculations take a great deal of time because the completed artillery tables must take into account different adjustments in elevation and field atmospheric conditions. The successful deployment of the computer cut the work cycle time to seconds from minutes, hours, weeks, and even months.

Moore's law continues to speed up this useful work cycle so that now similar calculations can be made in billionths or trillionths of a second. The work that the energy of the computer can accomplish in useful work cycles is so extraordinary that humans are beginning to write programs in any possible area that might take advantage of the inherent speed advantage.

Many of the powerful uses of programming speed took a while for humans to understand and utilize. First they had to construct programming languages to help them write and run programs. Then they had to begin to develop the field of artificial intelligence which helped them to understand how to use this speed to mimic human learning. One of the earliest experiments was to teach a computer how to play chess. Another was the development of flight simulators that could train humans to fly large expensive aircraft and perform maneuvers that would be too dangerous to otherwise afford.

The speed advantage of using a computer can dwarf the difficulties of developing the software whenever there are enough users to amortize the cost of development. Word processing is an excellent example. From the moment a human strikes a key there are over 200 programming steps that have to be run before the letter appears on the screen, but the speed of the computer is such that these steps appear to be instantaneous and are worth the time and expense of programming because of the benefits they offer a typist using a word processing program.

Similarly humans generally do not notice that every work cycle has a **physical component** required to guide the available energy into a useful format. Cooking requires access to fire, combustion, or heat in some form from a heat source such as wood, gas, coal, oil, or electricity. This heat must be focused by a stove, fireplace, oven, or some physical format that directs the heat to the food usually held by another physical device such as a pot, pan, grill, or spit. James Watt struggled for twenty years (1765-1785) to shape metals into a physical format that would produce a better steam engine to transform the energy of heat into an engine that could produce 60 horsepower to power pumps, mills, and factories. Years of further experimentation after 1800 modified the machines to fit in ships and trains. The work sequence used by steam and internal combustion engines is fixed (programmed) by the design of the hardware. Changes in the machine design that controlled the time and amount of energy generated in each useful work cycle can take decades.

Computers and Software

Computers have a major advantage over other machines because although their capabilities are fixed at the time of their manufacture, they have the capability of **changing their programming work sequence through using "software" instead of "hardware" to redirect the energy into different tasks.** Software's great advantage is its ability to make the physical changes electronically using the speed of light to redirect the path of electrons in magnetic fields instead of building a new metallic device for every desired change. In computers the physical component being changed is a charge that is stored in a memory and can be changed electronically to redirect the work cycles that run at billions and trillions times a second. Part of the work cycle is physically fixed, or hard-wired, into a permanent instruction set any one of which can be turned on. We see a similar apparatus in action when we turn on a light switch which is hard wired to turn on certain circuits and their lights, or a lawn sprinkler system that can turn on certain zones of sprinklers. The advantages of a computer are its ability to turn on or off certain programmed work sequences with blinding speed and cascade them into a useful work sequence for the user, but most of all, to change them with a command from software rather than having to rewire the light circuits or dig up and construct new fixed zones for the sprinklers. In this manner, each work cycle follows the directions of the software stored in changeable programs in memory as the software commands manipulate the fixed instruction set options.

This capability allows anyone who owns a computer to write new programs to do useful work in areas of his or areas of interest without having to physically construct new machines**.** They also have the capability of transferring their programs to new machines that are less expensive and more powerful as they become available. Herein lies the **second great advantage** of computers**. They are able to use programmers to change the programming portion of their physical format to redirect the energy work cycles without having to construct new machines.** In fact, the first microprocessor computer chip was built by Intel for Busicom, a Japanese company that requested that they build twelve custom chips for a new product line of electronic calculators late in 1969. The Intel engineers realized that if they built a new single programmable general purpose logic chip, that this one chip could be changed by programmers to fit different designs for the calculator line instead of requiring new and different chips for each component and product.

A third advantage of computers is the **replicability or scalability of their programs** that can be stored on small portable storage devices such as CDs, DVDs, small disk drives, or solid state devices such as compact flash cards. These storage devices can be used for acquiring or updating useful programs in every area from finance to entertainment where they can then be inexpensively distributed to the computers throughout the world.

Nanotechnology and Quantum Computing

Two of the current candidates for new energy sources in the future are **nanomachines** and the **quantum computer.** The great physicist Richard Feynman posited the idea of building tiny machines at the molecular level in a speech in 1959. Billions of tiny machines constructed at the atomic and molecular level could unleash enormous sources of power in extremely portable formats. Since then the field of quantum computing has also emerged as a serious pursuit. Some scientists believe that the year quantum computing becomes a possibility, computers will not grow 50% in potential (their current rate), but will have a billion times the computational power.

The Internet

By the mid 1990s another technological breakthrough occurred, **the Internet**, which allowed people to begin to connect their computers to a world-wide network which helped demolish barriers of distance. Suddenly people could download their software without using a portable device, and for the first time in history people had access to computer programs from their home, workplace, or portable telephone that allowed them to use and/interact with these programs. Hitherto using the speed of light they had been able to talk on telephones, listen to radio, or view television, but as exciting as these devices were, each lacked some fundamental attribute that restricted access to an important capability.

For example both radio and television keep the viewer passive and unable to respond to the programming or control its sequence. The listener or viewer can change stations or channels but not the sequence of the scheduled program which relentlessly follows its programmed sequence. He or she cannot interrupt them with questions or requests for clarification or give answers that need a response. The telephone offers the interactive potential that the television and radio programs lack, but it has four serious limitations in that: (1) it requires the availability of the person being called; (2) limits the caliber of the information available to the intelligence and verbal abilities of the person being contacted; (3) leaves no permanent record that can be accessed again; and (4) is a non-scalable activity requiring a one on one commitment of two people for the period of the phone call.

Thus a phone call erases the barriers of distance but otherwise has limited productivity and quality.Although the verbal response from someone being called can contain critically important information, for the most part, it is not nearly as powerful as professionally crafted programs that bring resources to bear that the average person talking on the phone cannot match. Compare the verbal description of a person on the phone describing a movie with the impact of actually viewing the movie on a large screen accompanied by stereo sound, or compare the quality of person’s voice singing a greeting to a friend on the phone with the sound of a professional orchestra and vocalist on an iPod. Convenience does not always mean quality.

The Internet will allow us to combine the strengths of the various technologies and avoid the weaknesses inherent in their separate approaches. Above all else, the

Internet will expand the depth of **access** available to powerful programs and the ability to **interact** with them in almost any setting throughout the world. This access to a **new source of energy** will cause a revolution in education that will rival the impact of the Fertile Crescent food package or the Industrial Revolution on the destiny of the human race because it will have the capability to provide virtual evolutionary advantages for those that have access to the educational packages.

The Importance of Education

Humans currently lack the ability to improve the genes they are born with, but through education they can improve their capability to use their genetic heritage wisely and well. As humans are educated, they become capable of producing more effective work for their benefit and survival much as a computer becomes infinitely more useful and effective as it acquires new software upgrades. Our goal in education is to give to all children the best education possible to enhance their given talents to insure that they live rich, productive and useful lives. Education is the one hope we have for improving our "fixed assets."

The Sources of Energy in Traditional Education

There are two traditional sources of energy in education: human manual workers and their technologies. There are three manual workers whose energy is utilized: the **parents**, the **teachers**, and the **students** themselves. The parent and teacher energy is directed by stored energy in the form of knowledge that is the result of their education and their access to books and educational materials. The technologies that have traditionally supported the parents and teachers are primarily technologies that write, display, and store information (stored energy) to help their active but transient efforts. Typical of these technologies are books, papers, pencils, blackboards, chalk, overhead projectors, TVs etc. These are effective because they scale information inexpensively, but they are limited because they are a form of passive stored energy that depends on being noticed and understood by the student; these forms cannot initiate activities or interact with the student and branch to an appropriate response based on the knowledge of the student's understanding and needs.

Destroying the Educational Access Barrier Through the Use of Technology

Currently access to a first-rate education is expensive to acquire and restricted to those that have great schools available in their culture. But the Internet will change this. The evolution of the availability of music for the general population suggests the pattern that will be followed in education. Years ago only a few people had access to music, and if the general public wanted to listen to music, individuals would have to travel to a distant setting and listen to a performance. Currently access to education for most people requires that they leave their homes, travel, and sit through a series of "performances" by teachers. In both cases the cost and time commitments are considerable because the experience requires the presence of trained experts in carefully scheduled blocks of time performing to an audience that has spent significant time on sleeping, eating, grooming, and traveling to the site before the performance. Then after the performance they will have to spend additional time traveling home and are denied further access until they can travel back again. In both musical and educational performances the participants are restricted most of the time to a passive status during the performance, although in well-run schools students can have some personal interactive moments from the teacher. Unfortunately these moments are much less frequent than the public envisions. One of our favorite metaphors of school is the image of a loving teacher interacting with a student. But some careful and important research in the early elementary grades by Eaton Conant in the early 1970s (*Teacher and Paraprofessional Work Productivity)* revealed three devastating facts:

- **Only 26% of the class time is spent on instruction.** The rest of the time goes to managing the children, a task that has been likened to herding puppies.
- **The general limit for most students is one minute a day of individual instruction.** This is not surprising considering that there are, according to Conant, only approximately 93 minutes of instruction available for the class in a 360 minute school day. If we assume that Conant's statistics hold for older students through high school, then in a 180 school day year students receive only 180 minutes, or half a school day a year. From the

time a student enters elementary school and graduates from high school 12 or 13 years later, he or she has had less than a week of individual instruction.

- **Adding a paraprofessional to the class adds little additional individual instruction for the children**. As Conant found, adding a second adult to the class does little to improve student individualization and is unimpeachable proof of the folly of trying to improve a manual system by constantly adding more people to the delivery system. They cannot generate enough additional work to improve individualization for the students.

So much for our favorite metaphor of a loving teacher with an arm around a student dispensing individual instruction. But understanding this unpleasant limit helps us suddenly realize in a "eureka" moment a stunning solution suggested by the music analogy.

When humans invented technologies that could harness the energy and the speed of light with radio waves from the electromagnetic spectrum, suddenly they could listen to any music they desired at any time in their homes and cars over the radio and even watch performances over television. They no longer had to leave their homes and travel to hear performances. Portable devices such as records, tapes, and CDs added further options as the music was designed to play on ever smaller portable devices such as transistor radios, Walkmen, and now iPods. **The democratization of music** followed from harnessing the power of electricity and the speed of light to allow anyone to listen to any music at any time or place.

In a similar manner the **democratization of education** is about to take place as many of the mechanisms involved that were invented to carry music are coupled with the power of the computer and the Internet to distribute interactive education to children and adults in their homes. Education requires a computer to instruct the student at an appropriate level, judge the validity of the student response, branch to new instructions that fit the student's needs at that moment, and then compile and organize reports for the student, parent, or teacher on the status of the student's learning. The Internet will provide a highway to distribute the materials in real time with two way interactions to students at home anytime of the day or night, any day of the week, and in any state of dress or undress.

Furthermore (and most importantly), with the help of the energy and speed of light as outstanding software is constructed in the years ahead, the quality of the individualized interactive instruction will gradually transcend what many students have available in their preschools and schools. As computers grow in speed and storage, undreamed of instructional capabilities will emerge:

(1) As speech recognition is perfected, students will be able to have a conversation with the computer which will act as a surrogate tutor for them, a surrogate tutor that gradually compiles the wisdom, knowledge, and examples of millions of the best teachers in the world.

(2) A tutor that is available anytime, anyplace, with a scientifically sequenced curriculum that represents the finest curriculum that experts can design.

(3) A tutor that builds a data base of knowledge about each student's learning style and constructs a learner profile that guides the instruction presented to the child.

(4) A tutor that understands the science of learning and can adjust to the most sophisticated learning problems and patiently and expertly offer the precise individual instruction enhanced by beautiful artistically developed life-like characters set in exciting stories that are appropriate and motivating to the child's needs at that time.

(5) A tutor that is linked to a data base working interactively with millions of students where research will gradually improve the knowledge and science of learning and upgrade the tutor's capabilities in real time.

Clues from the Experts

Over the past 30 years as I have tried to understand the full implications of energy and work for success in education, I have read deeply in many disciplines and learned that historians, economists, technologists, futurists, anthropologists, sociologists, psychologists, medical researchers, linguists, business leaders, and scientists (among others) have much to teach us about the future because it tends to be a variant of the past. I have found it useful to study the insights of some of our best thinkers who have been analyzing the educational delivery system from fresh points of view because they believe that the education of human capital is fundamental to our future survival. These views come from everyone from Nobel Laureates and denizens of think tanks, to government bureaucrats, reporters, social commentators, and even businessmen who with great honesty and integrity have offered invaluable data and ideas.

Having discovered the importance of education, the value of knowledge, and the benefits that technology offers in producing economic growth, the **economists** are poised to offer some of the most knowledgeable commentary on strategies to utilize our educational capital most wisely. One of their most important contributions is their recognition of the importance of technology in generating growth. Most humanists are intimidated by technology, but the economists appreciate its ability to increase productivity and drive economic growth which in turn is invaluable to a culture.

Unfortunately they have not yet noticed the potential of technology to educate human capital in the most efficient, pleasurable, and inexpensive way. Currently they are applying their considerable analytical, statistical, and economic skills trying to improve our educational delivery system with recommendations that assume the current energy profile is fixed by the limitations of a manual delivery system. But once they realize the potential of the new technologies to exponentiate the available energy for teaching and improving human capital, they will be of great help because they understand the role technology has played historically in compounding the available energy in classical delivery systems such as agriculture, transportation, communications, and the military. They have the ability to understand the potential productivity gains that technology offers.

Robert Solow

Robert Solow of MIT is an economist who in 1956 and 1957 wrote two articles on the sources of economic growth which led to his Noble Prize in economics. His research showed that in addition to the traditional inputs of labor and capital some new unidentified input was generating more growth than was predicted by traditional economic models. He realized that this unknown factor had caused 7/8ths of the doubling of output per hour of workers between 1909 and 1949. He decided that this additional input was “technological change” and admitted that did not understand the mechanisms behind it.

His discovery began to focus economic thought on the implications of how knowledge and technology create economic growth.

Paul Romer

Over 30 years later Paul Romer at Stanford wrote a remarkable paper in 1990 that has had a significant impact on economic thought by clarifying the importance and potential of knowledge and technology to produce sustainable accelerating growth for a nation. In this paper he explains and clarifies mathematically the growth phenomenon noticed by Solow and explains how it fits within the traditional framework of economics. Solow noticed the phenomenon and Romer explains it and places it inside traditional economic thought.

But Romer also understands the extraordinary leverage that accrues with growth, particularly growth that is compounding. In his words,

> In the modern version of an old legend, an investment banker asks to be paid by placing one penny on the first square of a chess board, two pennies on the second square, four on the third, etc. If the banker had asked that only the white squares be used, the initial penny would double in value thirty-one times, leaving $2l.5 million on the last square. Using both the black and the white squares makes the penny grow to $92,000,000 billion.
>
> People are reasonably good at forming estimates based on addition, but for operations such as compounding that depend on repeated multiplication, we systematically underestimate how fast things grow. As a result we often lose sight of how important the average rate of growth is for an economy. For an investment banker the choice between a payment that doubles with every square on the chess board and one that doubles with every other square is more important than any other part of the contract. Who cares whether the payment is in pennies, pounds, or pesos? For a nation the choices that determine whether income doubles ever generation, or instead with every other generation, **dwarf all other policy concerns**.

Since computers are following the same doubling phenomenon at a blistering pace (they have passed their 20th doubling of power and storage over the past 40+ years), Waterford believes their doubling, in Romer’s words, will ultimately “dwarf all other policy concerns” in the education of children because of the energy they will add to the educational delivery system.

Romer helps us understand the importance of knowledge, ideas, and innovation; whereas, traditional economics labor, capital, and physical resources. Romer is uncomfortable with “scarcity economics” which assumes that our basic resources are finite and are used up as we expend them with attending higher prices and decreasing returns. He prefers a metaphor that values education and the training of human capital to empower humans to innovate and invent new products and solutions from the 100 or so elements found on our planet. He believes human innovation can develop almost an infinite number of new products from the elements by experimenting with different variables such as temperature, pressure and the sequence followed as they are combined or mixed. He likens the process to the way we have learned to cook available foods and develop recipes which require the mixing of them with specific sequences and temperatures.

Romer also understands that although humans are not scalable, their ideas and software are. Furthermore as they are shared and scaled, they are not used up. In fact the more they are used and shared, the more they create abundance rather than scarcity. Human capital is important because it can invent almost limitless ways to develop useful products to aid all humans.

He is so impressed by the scalability of software in an educational delivery system that he raised millions of dollars to form a company to develop and sell software for college economic classes. Better than any other economist, Romer understands the economic implications of developing and scaling educational software.

Romer’s heritage leaves us with an increasing respect for information, knowledge, and innovation which continue to generate increasing returns over time rather than trusting in the efficacy of growth from physical objects and resources which become scarce and expensive as they are used up. **Ideas** are more important than **things** for generating economic growth because they can invent new products and industries, and the more they are used and improved, the more they grow, spread, and generate prosperity for a nation. In short the more the use, the greater the return. This is the opposite of the use of physical resources where use causes scarcity and decreasing returns.

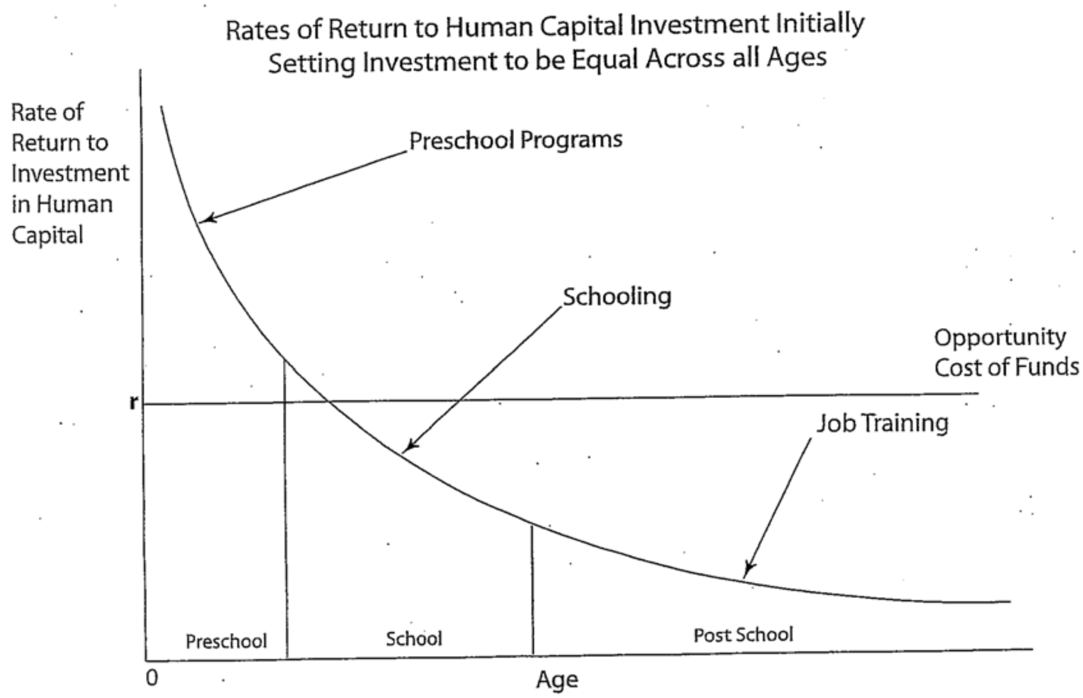
Romer believes that the development of policies that contribute to the genesis and spread of ideas, knowledge, and innovation is one of government's most important functions. In order to assure a country's economic success, the government must subsidize education, reward innovation, and provide short term protection of intellectual property. This will provide the incentive to innovate and discover new ways to develop our physical assets which are the 100 elements and the laws of the forces that govern them, and not necessarily a given formulation of them in nature such as oil or ore. There is an almost infinity of options available to combine the elements and the forces that control them in various amounts, ratios, temperatures, pressures and sequences.

James J. Heckman

Some of our best economists are turning their attention to education. For example James J. Heckman won the Nobel Prize in economics in 2000 for his work in developing new algorithms for measuring economic data at a much finer level than previously possible (microeconomics). His research, with the help of the computational power of computers, has led to more accurate analysis of the implications of various public policies and clarified the most efficient approaches for some of them. This has been helpful in guiding decision makers in a number of fields, and he has written some excellent materials on education.

What his data clarify is the **importance of working with young children**. In his words from his paper on "Human Capital Policy" he writes, "The evidence points to a high return to early interventions and a low return to remedial or compensatory interventions later in the life cycle. Skill and ability beget future skill and ability." In an exquisitely clear diagram he and his co-author Carneiro clarify the economic and educational return in concentrating on the preschool years.

THE HECKMAN/CARNEIRO DIAGRAM



Rates of Return to Human Capital Investment Initially Setting Investment to be Equal Across all Ages

Heckman makes a strong case for concentrating more efforts on the early preschool years, and Waterford believes the implications for technologists and their supporters are twofold:

(1) Powerful educational software needs to be constructed for young preschool children beginning at age two or three.

(2) The materials will have to be deliverable to the child at home as well as in preschools because not all children will be well situated in preschools with adequate instructional capabilities. Given these constraints, the Internet will be the logical choice to deliver the materials. The government will have to subsidize these services as an extension of the concept of public education in order to insure that all have access to them.

Betty Hart and Todd Risley

Other scholars support the need for early interventions. For example Todd Risley and Betty Hart reported in their 1995 book (*Meaningful Differences*) their devastating findings concerning the number of words that welfare family children have spoken to them by age four in comparison to children who were raised by parents who worked in the professions. They had been led to studying very young children in their home settings to help explain the puzzling failure of Lyndon Johnson's Great Society programs that had unleashed generous funding to improve the elementary school performance of the low SES (socioeconomic status) children. They found that the primary reason the reforms were not working was that they were being introduced too late. By age four the welfare children had been spoken to **32,000,000 words less** than the children of the professional parents (13,000,000 vs. 45,000,000). Furthermore, the tone of the comments to the children from the parents was 6:1 positive in the homes of professionals and 2:1 negative in the welfare homes. They also noted that the professional families assumed the importance of teaching abstract symbol sets and decision making when little, if any, of this took place in the welfare homes.

These findings from Heckman, Hart and Risley suggest that the most productive time to introduce the use of the energy from the new technologies is during the early years of a child's growth before the formal schooling begins in Kindergarten. This also suggests that the new technologies should be available both in home and preschool settings.

Herbert Walberg, Keith Stanovich, and the "Matthew Effect"

Herb Walberg is an educational researcher who specializes in the meta-analysis of other scholars' work. He will conglomerate the findings of a group of scholars in a given area, such as the impact of class size on student achievement, and summarize the implications of their findings. In 1983 he reported with another scholar, S.L Tsai, on what he called "Matthew Effects in Education" that suggested a devastating finding that was emerging from an analysis of scholarly literature about the fate of young children who were delayed in receiving competent preliteracy and literacy instruction in their homes, preschools, or early elementary grades. The delay is not a minor issue, and not only is it almost impossible to make up, but it seems in a malignant manner to compound against the children's chances for educational success.

To explain the dreadful implications of this delay, they used the phrase "Matthew Effect" from Matthew 13:12 in the New Testament. In Matthew's words, **For whosoever hath, to him shall be given, and he shall have more abundance: but**

whosoever hath not, from him shall be taken away even that he has. In context Christ is describing the plight of those who are incapable of understanding something of priceless value where they **seeing see not; and hearing hear not, neither do they understand.** This brilliantly spells out the consequences of failing to learn core concepts at the appropriate time. The impact has double consequences to the unfortunate individuals as time plays out, for not only do they fail to achieve appropriate growth, but even worse, they seem to lose what they have. In a perverse way people seem to require an advantage to gain an advantage, and once gaining the advantage, they can compound this advantage in their favor while those without seem to dwindle in terms of potential.

In 1986, three years after the Walberg and Tsai article, one of the leading **reading** research scholars in the world, Keith Stanovich, published a painful and moving scholarly masterpiece where he analyzed the Matthew Effect specifically in the field of reading and spelled out "some consequences of individual differences in the acquisition of literacy." The data he collected echo the Matthew paradox: Those students who get a great start benefit from an accelerating upward learning curve where a host of important learning tasks, including higher order thinking skills, automatically compound in their favor, while those who are denied them begin a destructive path which compounds against them and leads to such miserable experiences in schools that they form the nucleus of tomorrow's dropouts. Clearly the early years have a significance that we must plan for and acknowledge.

Valerie E. Lee and David T. Burkam

Additional supporting data comes from Valerie E. Lee and David T. Burkam at the University of Michigan who have contributed to the understanding of the problems of inequity at the start of Kindergarten in a book they published in 2002 entitled *Inequity at the Starting Gate*. Their conclusions were based on an analysis of the Kindergarten Cohort of the U.S. Department of Education's Early Childhood Longitudinal Study where they reported differences in young children's achievement scores in literacy and mathematics by race, ethnicity, and socioeconomic status (SES) as they started kindergarten. They found profound differences before formal schooling even started. For example:

- By the start of kindergarten the average scores of the children in the highest SES group are 60% above the lowest SES group.
- The average math achievement is 21% lower for Blacks than for Whites and 19% lower for Hispanics.
- 34 % of the Black students, 29% of the Hispanic students, and only 9% of the White students are in the lowest 5th of the SES group.
- Similarly, 48% of families in the lowest 5th of the SES group are headed by a single parent while only 10% of the single parent families are found in the upper 5th SES group.
- 15% of the White children, 54% of the Black children, and 27% of the Hispanic children live in single parent homes.

Once again we can see the importance of working with the children before they enter school, particularly if the family is led by a single parent.

Ron Haskins

Another analyst, Ron Haskins, has helped clarify some of the educational issues in the context of low SES families. Haskins is a scholar who has worked as a university researcher and as an economic consultant for government agencies, the White House, congressional committees, think tanks, and foundations. His expertise relates to families, children, welfare, and children's education. One of his strengths is his ability to offer a balanced view of the strengths and weakness of various government policies and reforms. He noted in testimony to a Congressional Committee in October of 2005, the single parent problem cited in Lee and Burkam's study is continuing to grow.

> One of the first social scientists to notice these developments was an obscure sociologist in the Department of Labor by the name of Daniel Patrick Moynihan. In 1965 he wrote a famous paper on the black family, arguing that family dissolution was the major reason black Americans were not making more social and economic progress in America. At that time the nonmarital birth rate for blacks was around 25 percent. Today the percentage for blacks is 70. Now both Hispanics, at about 45 percent, and whites, at about 25 percent, equal or exceed the level of nonmarital births that Moynihan saw as alarming. Indeed, over 33 percent of all our nation's

> children are now born outside marriage – well above the rate Moynihan
> saw as alarming in 1965.

The stress the single parent faces in raising children adds to the difficulty of providing single parent and low SES homes with a quality education for their children. The welfare reform enacted in 1996 has improved the financial condition of some of the poorest families, but this has not always contributed to the children's educational improvement. Haskins noted in 2002 that "child poverty has dropped quickly, reaching its lowest level in 20 years" as "2.5 million fewer families are getting cash welfare." But in order to accomplish this, the children of the single parent working mother must attend daycare or enroll in Early Head Start (age 3) or Head Start (age 4) programs. As we will see in Loeb's PACE study, there appear to be mixed blessings for children attending preschools where their impact suggests that the students may face a tradeoff between cognitive and social gains. Thus children might grow in cognitive skills as a result of their preschool attendance, but also might find the experience (compared to staying at home) so frustrating that they begin to develop social behavioral problems.

Waterford believes that a supplemental technology based program available to the children both at home (starting at age two) and in their preschools can achieve the needed cognitive goals and may contribute to aiding the social goals as well. Some of their social frustration may be a result of their feeling uncomfortable in a learning setting where they are functioning with only modest success, if at all. The hallmark of the new technologies will be their capability to insure educational success for most children. Given the reality of the bleak home picture portrayed for many preschool children, and the importance of raising their cognitive skills in order to maintain their future educational mobility, the best hope we have is to follow the Heckman/Carneiro recommendations and concentrate our resources on our youngest children before they enter formal schooling.

Here the new energy sources from the Internet and the computer focused on the home could revolutionize education if preschool children could gain access to these powerful new programs prior to their starting kindergarten. Recall that in previous epochs when a dramatic new source of energy becomes available, extraordinary benefits accrue to that culture taking advantage of the new energy technologies.

Critics of this position might argue that there is a successful government program already addressing this need called **Head Start** which is serving almost a million four year-olds at a cost of $7,000 -$9,500 a child. Ron Haskins has an excellent article on the history of Head Start called “Competing Visions” published in 2004 that acknowledges its great strengths but also points out that while it clearly has been successful in some areas, there is little evidence that it is has served the academic goals the founders hoped for in preparing the four year olds for academic success in school. He summarizes the hard data:

> Data on school readiness for children entering Head Start in 1997 and 2001 show that children start the program with test scores far below average. Their performance improves slightly after a year in Head Start, but not enough to make a real difference in the achievement gap. These striking differences upon the completion of Head Start translate into equally stark differences in school-age test scores, high-school graduation rates, college attendance, and earnings in the workforce.

Cognizant that one year of preschool may not offer enough academic support to the low SES families, Head Start proponents have opened a program for three-year olds called Early Head Start in hopes that more exposure to a preschool setting will help close the divide that precludes many of the children from having an equal start. There is recognition that these young preschool children need more quality instructional time, but this is not easily achievable in a Head Start or preschool setting where both the available expertise and the environment work against it. The teachers usually lack the necessary training to teach the young children with the sophisticated skills required for successful early reading instruction. The setting, where the teachers at times face an unruly audience, is not able to provide what is most needed: individual cognitive instruction appropriate to each child’s needs. We know that in the early elementary school years children are limited to about one minute a day of individual instruction in a system designed to offer formal instruction, so the preschool settings (where there are many non-academic goals emphasized) there is not even a minute a day available. And we know that typical Head Start program is open less than half the days in a year.

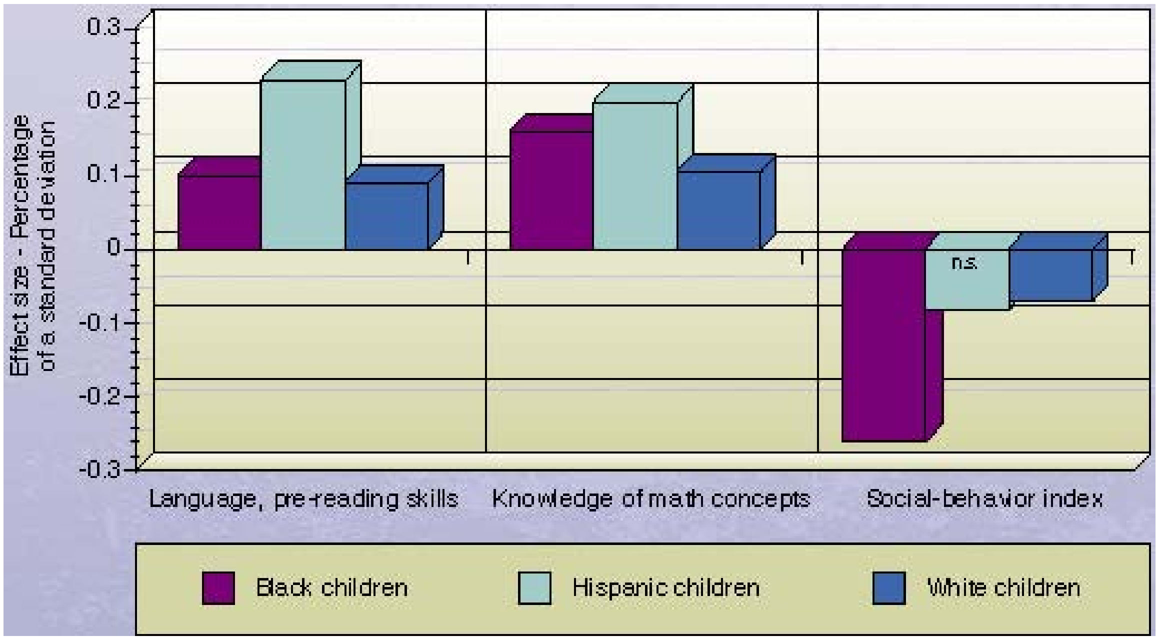
What is needed is a new source of energy and work that can offer the necessary expertise to provide as much individual, interactive, artistically pleasing instruction as each child needs in a setting where the child will have much more time available to receive the instruction. Fortunately this condition is emerging as the Internet is connected to more and more homes and preschools.

Susanna Loeb

Drawing on the same data from the same Kindergarten cohort of the U.S. Department of Education Early Childhood Longitudinal Study used by Lee and Burkam from the University of Michigan cited above, Susanna Loeb of Stanford University and other PACE (Policy Analysis for California Education) scholars from Stanford, Berkeley, and U.C. Santa Barbara reviewed information from over 14,000 preschool attendees and discovered both **positive cognitive effects** and some **negative social effects** from preschool attendance. Loeb is another trained economist who is using her analytical and statistical skills on behalf of education. Their findings suggest there are some modest cognitive advantages for children who attend preschools, and that the greatest cognitive growth takes place with children who start programs **between the ages two and three**. This is very useful information, but she also cautions that there are negative social effects for children who attend preschools as compared to students who stay at home, particularly for African American students.

Here technology may offer a solution to help these children. Those students who are negatively impacted in their social growth might do better to attend formal preschool programs less and have more time at home with family members or other caregivers with the Internet software training their cognitive skills.

As Loeb's diagram below indicates, although most students benefit cognitively from preschool attendance, as a group they are negatively impacted socially, and the African American students in particular have negative behavioral effects associated with preschool attendance.



An Internet option delivering instruction to the home could be of great benefit to children who are exhibiting social behavior problems because of the long hours they are spending in preschools. The availability of additional individualized interactive instruction using colorful graphics and animation could both hold the children's attention and insure mastery of the subject matter.

There is also the possibility that some of the social problems the children are experiencing are not only caused by being away from their family setting, but also by their difficulty in feeling comfortable in what to them is an academic atmosphere where learning verbal and mathematical skills is not easy because of the lack of early family work on their behalf. Recall that by age 4 most of the low SES children have had 32,000,000 less words spoken to them than their more affluent peers, and since they tend to associate verbal expression with negative comments (two-thirds of the words spoken to them are negative in tone), they might be reacting to an atmosphere where they are uncomfortable and not very proficient in mastering the skills of the preschool curriculum. In this case having the materials available at home where the software interactions are pleasant, carefully sequenced and offered with infinite patience, might simultaneously improve both their social and cognitive skills and prepare them to handle more school time without the negative social impact they are currently facing.

Robert Sampson

Sampson is chairman of the sociology department at Harvard who has been studying the social ecology of urban environments and has contributed to our understanding of some of the difficulties faced by the poorest urban families. Recently he published an important seven year study of 2000 young students from Chicago with a colleague from Chicago (Stephen Raudenbush) and New York (Patrick Sharkey) in the *Proceedings of the National Academy of Sciences* in January 2008 that delineates the academic damage caused to African American children raised in poor and dangerous neighborhoods in Chicago.

His data clarify the educational impact on young children who are raised in relative isolation in the unsafe neighborhoods because of the street violence that restricts normal social activity for the children. This isolation dramatically reduced the children's access to a rich and varied vocabulary, and especially what the author's label **academic English**. In tracking the children's academic progress over a 7 year period beginning at age 6, the team noticed that half way through their observation period the children had lost 4 IQ points in their verbal ability which is equivalent to at least a full year of schooling, and possibly as much as two. One year in schooling "has been associated with between a 2- and 4- point gain in IQ." And even if the students move to better neighborhoods, the negative effects of the early experience tend to persist.

Sampson has also discovered the need for a strong sense of community to provide social cohesion for the neighborhood. Where there is cohesion there is less crime and violence. And most interestingly, given Waterford's nonprofit mission, Sampson notes nonprofits can have a significant impact. "We've shown that, more so than poverty, more so than racial composition, even more so than the nature of social ties among people, that the density of nonprofit organizations is very strongly predictive of the rate of collective action."

I believe Sampson's work suggests that the ability to provide young children living in isolation amidst violence with a safe means of gaining access to outstanding academic training in preliteracy activities in their homes is another example of how the new technologies will help solve the problems that are currently leaving children at serious academic risk. In fact, in a perverse way, having a stimulating educational experience available for children at home who are forced to live in social isolation for personal safety might motivate many of them to work with the materials far more than the recommended 15-20 minutes a day. This additional time could help prepare them better academically than some of their more fortunate peers.

Most people are unaware that many of these children are so far behind in their vocabulary training that they are essentially uneducable as they enter kindergarten classes in many inner city schools. Thus these schools struggle to graduate at least half of their students from high school while their suburban neighbors usually graduate over 80% of their students. Remember that compared with the children from a higher economic bracket, they have been spoken to 32,000,000 words less by their 4th birthday, have experienced less than 7% of the preliteracy training from their families, are spoken to negatively by adults 2/3rds of the time, and are losing at least 4 IQ points because of their lack of access to academic English in their family settings.

An interesting by-product of placing the Internet connected hardware in the homes of the poorest families is that a "portal" to the outside world could be established that could serve as a platform to provide the families the services of many nonprofit and governmental agencies. If Sampson is right, then having access to some of the services of these nonprofit and governmental organizations in these communities should strengthen community ties and lower crime and violence. All the members of the families could benefit from the training, education, information, and services available from the various agencies on the Internet. Instead of having community access to only toxic experiences outside the home, they could have access to instruction for the children, training for the adults, and the ability to communicate with many nonprofit and governmental agencies over the Internet.

With proper training they could also be introduced to the rich world that the Internet and email can offer to the family. Obviously proper safeguards against the use of pornography could be part of the home package. By supplying these services for free, the city and state and federal governments could provide the motivating spark for the families to use the services wisely and well for their children by making the child's usage a condition of having the free services continue.

One of the greatest benefits of technology is the low cost associated with its usage. Legislatures will gradually begin to understand they will be able to offer these extraordinary services for less than 10% of any manual option which requires formal organizations to provide personnel to work directly with the children and families such as preschools, Head Start, Early Head Start, family visiting services, etc. They will also have the pleasant discovery that the teaching and training will be available at all times and not just at a specific time and place at the convenience of the teacher or visiting expert. Furthermore overly burdened parents will be spared the difficulty of travelling with their children to find access to many of the services they desire.

Erik Hanushek

Another economist, Eric Hanushek, is making major contributions in policy debates about educational funding and efficiencies. As is true of many well-trained economists, he has the ability to analyze statistics and find the significant causal issues behind them. This type of knowledge is important because many of our embedded educational assumptions do not hold up under scientific scrutiny. For example there does not seem to be a strong correlation between the amount of money being spent per pupil and its measurable educational effectiveness. Similarly, with the exception of some modest growth in small kindergarten classes, smaller class size has very little educational validity even though it is near and dear to our hearts.

Drawing on decades of experience in analyzing the economics of growth, Hanushek makes an excellent case for why economists are using their skills to further excellence in education in an article on economic outcomes and school quality. He notes

Human capital is a powerful force
driving economic growth.

> The human capital of the population, which is enhanced by a strong education system, enters directly and indirectly into economic growth. Education has the possibility of making both the individuals receiving it and others better off. Specifically, a more educated society may lead to higher rates of invention; may make everybody more productive through the ability of firms to introduce new and better production methods; and may lead to more rapid introduction of new technologies. These

> “externalities” – influences on others of individual education outcomes - provide extra reason for being concerned about the quality of schooling.

What Hanushek is advocating is that we study what works educationally before indiscriminately pouring more money into the current delivery system. He is particularly sensitive to the proclivity of judges, under the guise of a lawsuit demanding equality for different constituencies, ordering large amounts of money to be given to school districts as they currently are structured because there is no evidence that additional funds will have a positive impact. In his words, “Addressing these problems by simply augmenting the current system, which has virtually nonexistent performance incentives, will not solve the problems.” An economist’s nightmare is heavy expenditures without proof of its value and a lack of incentives for performance.

He notes that in New York State a judge has ordered the state to give an additional $5.6 billion per year (more than $5,000 per student) to New York City to a system that is already spending about $13 billion in operating revenues, or almost $13,000 a student. New York City, he summarizes, is already is spending “more than 50 percent above the national average and pulling away.” His great concern with such a proposed system is that “it purports to provide something that cannot currently be provided: a scientific assessment of what spending is needed to bring about dramatic improvements in student performance” because it provides “little information about the costs of achieving improvements efficiently.” In short, “They contain nary a word about changing the reward structure for teachers (other than paying everybody more). They avoid any consideration of accountability systems based on student outcomes. And they lack any appropriate empirical basis.” In his view if the 43 % increase demanded by the judge remains in force, it will be just as effective as the 44% increase already put in place by the New York City school system from 1998 to 2003 with the usual mixed results: fourth grade went up slightly while 8th grade went down.

Hanushek is committed to improving schools because he believes data suggest that “school quality has a remarkable impact on differences in economic growth,” and that three studies from Chicago, Harvard, and Stanford “provide direct estimates of the effect of test performance on earnings.” Thus he is keen to clarify the metrics required to define what produces a quality education. His data suggest that if a “moderately strong improvement in student skills could be obtained during a 20-year reform period, a country could expect to pay for all of its educational expenditures by 2040 with the growth dividend.” He is committed to a long range strategy using an econometric model that compounds in favor of sustained growth policies. Hanushek believes that “Economic growth determines how much improvement will occur in the overall standard of living of society. Differences in growth rates that seem small can make a huge difference if maintained over a period of time. . . .Indeed, the current economic position of the United States and other developed countries is largely the result of these countries’ strong and steady growth over the second half of the 20th century.”

He realizes, however, that although economic growth is necessary and that “quality in education is directly linked to individual earning power and productivity,” that unfortunately at this time “there is a lack of any consistent or systematic effect of resources on student achievement.” In other words we do not yet know how to apply our resources to provide a quality education or improve student achievement. We know it matters and has a strong impact, but despite an almost universal belief that more money will always improve education, the data tell another story.

Paul David

Over the past 30 years as I have tried to understand the full implications of energy and work on education, I have read deeply in many disciplines and learned that historians, economists, technologists and columnists have much to teach us about the future because it will probably be a variant of the past. For example, Paul David, a Stanford economist, has written many excellent articles on economics and technology and is quite articulate about the potential of technology in accelerating and sustaining growth.

His analysis in his article on “The Dynamo and the Computer” (1990) is very helpful in clarifying the long time delay in the United States between the time new technology is introduced and gains in productivity follow. For example, although the light bulb was invented in 1879 and the first power station for generating electricity was built in 1881, there were no substantial productivity gains in the factories using electricity and electric motors until 40 years later in the 1920s. He suggests that we note “the existence of special difficulties in the commercialization of novel (information) technologies that need to be overcome before the mass of information-users can benefit in their roles as producers."

At the time David published his article on the dynamo and the computer in *The American Economic Review* in 1990, almost forty years had passed since the commercial introduction of the computer in the early 1950s. David's paper was in response to the economists' concerns that despite massive investments in computer technologies in America, there seemed to be a lack of productivity gains, and economists were discussing the "productivity paradox" with great gusto. As Solow who is discussed earlier in this paper dryly noted, "We see the computers everywhere but in the productivity statistics." The point of David's paper was to inform other economists that "many features of the so-called productivity paradox will be found to be neither so unprecedented nor so puzzling as they might otherwise appear" when approached from the perspective of economic history. In other words, just wait! It took forty years for electricity to have a productivity impact; productivity gains from computers **are** coming.

Just as David predicted, within two years and following the recession of 1991, sudden gains began appearing in the productivity indexes. Eleven years later in 2001 in a Discussion Paper for the Stanford Institute for Economic Policy Research with Moses Abramovitz (SIEPR Discussion Paper No. 01-05) David summed up the stunning productivity gains that were being realized. In fact, the gains from information and communications technologies (ICT) sector were so substantial that economists began to talk about "The New Economy." Typical of the commentary was an "Economic Letter" from the Federal Reserve Bank of San Francisco discussing the new economy.

> The increase in productivity growth rates beginning in the mid-1990s has helped boost economic growth and speed the rate at which living standards rise in the United States. Between 1995 and 2000, productivity growth averaged 2.8%--almost double the rate during the preceding 22 years! This increase in productivity growth is thought by many observers to be associated with the increased importance of information technology (IT), a hypotheses often referred to as the "New Economy" view (FRBSF Economic Letter 2001-14; May 11, 2001).

Another economist, Paul Krugman of Princeton, noted the same trend after reading the economic report in February 2000 issued by the President's economists, and he commented in his February 20th column in the New York Times called “Dynamo and Microchip” that their conclusion “that technology, not policy, is the main source of good news” is “surely right.”

> A technology-driven surge in worker productivity is directly responsible for about two-thirds of the acceleration in our economic growth from the 2.5 percent norm of the 70’s and 80’s to the 4 percent of recent years. The report plausibly argues that our unexpected ability to get unemployment down to 30-year lows without inflation is also an indirect result of the productivity boom. So there is no mystery about why we are doing so well: the microchip did it.

He notes that in trying to understand why it took the microprocessor revolution so long to have an impact, he remembered the Paul David article from a decade earlier that had impressed him and predicted this type of delay. So he dusted it off and read it again and decided it “makes even better reading today.”

Thus we learn an important lesson from David: introducing technology takes time, but once it clicks in it has an astonishing impact. This will be important to understand in tracking the potential of technology to help schools in America who have been struggling with the introduction of computers for about 30 years and should begin seeing productivity gains and success in schools in about 10 years if David’s assumptions hold true.

Clayton M. Christensen

The businessman-scholar Clayton Christensen has a clearer vision than most scholars of the implications of technology when it comes to changing and improving the educational delivery system. He has an interesting background that has prepared him to understand the disruptive impact of new technologies on what appear to be large, mature, and impregnable organizations such as big corporations or schools. He graduated from Brigham Young University after serving an LDS (Mormon) two year mission to Korea. Next, as a Rhodes Scholar he studied at Oxford before returning to the U.S. to study at the Harvard Business School where he received his MBA. Then he served as a consultant and product manager with the Boston Consulting Group for five years before co-founding Ceramic Process Systems (CPS), which develops products using high-technology metals and ceramics. Approaching the age of 40 a few years later, he decided he would rather become a teaching scholar and joined the Harvard Business School faculty after receiving his doctorate from Harvard in 1992.

In 1997 he published an award-winning book entitled *The Innovator's Dilemma* which brilliantly details the organizational pressures that the use of new technologies generates. In his analysis he has worked out the underlying laws that are unleashed when new technologies are introduced that are simple, convenient, and inexpensive enough to create new markets for users who can benefit from them even though initially they offer only limited and simple capabilities. The hallmarks of disruptive technologies are that they help people do a job that they would like done but would normally never undertake because they lack the expertise, time, or money to do so.

At first these simple technology products appear to be harmless and underpowered to the current market leaders who are experts in producing sophisticated products at high margins for their customers. Not only do the current market leaders miss the implications of the simpler product introductions, but often they are pleased to see them appear because they relieve them from having to support the lower margin end of their product lines.

Christensen labels these new products as "disruptive" because as they succeed, they frequently generate enough cash through high volume sales to allow management to keep improving their capabilities while keeping their prices down, or in some cases even lowering them. Then with low prices and margins, but also with increasing power and functionality, these disruptive products frequently morph into category killers that destroy the formerly impregnable market leaders that are helpless because their business models require high margins and continual growth.

Thus disruptive technologies end up damaging or even destroying market leaders. This has happened with computers (Mainframe to Minicomputers to Microcomputers), their disc drives (14 inch to 8 inch to 5.25 inch to 2.5 to 3.5 inch to 1.8 inch), vacuum tubes to transistors, typewriters to word processors, steam shovels to hydraulic machines, taken out the mini and mainframe computers, word processing snuffed out typewriters, small printers damaged the copy machine giants, and digital photography crippled the film and darkroom industry. In almost all cases the industry leaders lose their preeminent position because their values stop them from introducing the disruptive products themselves.

Christensen has not highlighted the importance of the new energy and work sources that technology harnesses as I have, but he is unique in defining the processes and laws that underlie their use so that managers are able to understand these forces and succeed in growing and strengthening their organizations rather than falling prey to being blindsided without understanding what is happening. In this sense Christensen is like a scientist who is offering a glimpse of the laws that determine organizational changes that follow from the introduction of rapidly evolving technologies and are difficult to see because their rapid cycles are counter-intuitive.

He is now extending his research to include organizations that have achieved near monopoly status (quasi-monopolies) such as school and medical delivery systems that appear to be impregnable but might find their monopoly status under siege because disruptive alternatives are appearing that provide their customers with an option that is simple, convenient and inexpensive. In this manner the near monopoly competitive fortress that is designed to withstand battering rams and elephants can be unexpectedly placed under siege by ants and termites.

One of the obvious quasi-monopolies that may be vulnerable to the gradual introduction of new technologies is the formal education establishment, and in particular, public schools. Because microcomputer hardware is improving at 1% a week (doubling every two years) without additional cost, schools will gradually gain access to additional technological resources that will enable them to offer individualized interactive instruction to their students in place of the approximate approach that is the only current viable option.

For example, a good rule of thumb is that there are as many years of difference in student abilities in an elementary class as the class grade level. Using this metric, there are three years of student ability difference in the third grade which stretches to eight years by the eighth grade. By the eighth grade some students will be reading at the fourth grade level and some at the twelfth grade level, providing an eight year span. Thus the teacher is forced to teach to an approximate level (the eighth grade) which terrifies the slower students (at the fourth grade level) and bores the brighter students (at the twelfth grade level).

The problem is that schools are unlikely to follow what Christensen labels this "promising path" until forced to do so by the appearance of competitive "disruptive" alternatives in the market which could undermine their parent tax support base that is maintaining their quasi-monopoly status.

Christensen's work suggests that once the software is developed, a new generation of disruptive software providers will emerge who will provide customized and individualized instruction to students who are not currently being served well by the approximate approach of the current educational system. The software will be delivered directly over the Internet to families and schools who want their children to have customized instruction available, or, alternatively, at least have the ability to supplement the generic approach available in schools.

As the home produces a new audience of users served by new organizations, the quasi-monopoly schools will naturally adopt the new software and technologies in order to compete with the disruptive alternatives and satisfy parents who will demand equivalent access to software for their children in the school system. They will not like their children who have been experiencing customized and individualized instruction at home via the Internet to enter schools where they will be constrained and trapped in classes where the only instructional level is an average one.

Thus empowering the home to have access to world-class customized and individualized interactive education will have severe organizational implications for schools. But as Christensen points out, public schools have been brilliant in adapting to changing requirements demanded of them by the generations they serve, and as the coming generations will demand customized education for their children now that the materials are available, they will respond by implement them in the schools.

Waterford believes that Christensen's emphasis on individualization is accurate, but that this demand for individualization will also have a strong impact on funding patterns from state legislatures. **What will be new is that as legislatures begin to understand the potential of using the assets of the home and families in conjunction with the new technologies in the early childhood years, they will extend their**

funding patterns to include preschool homes. Recall the advantages of the home which is open 365 days a year and requires no travel time to gain access to the instruction. The motivating advantage that legislatures will accept is that they will be able to provide customized instruction to the young children at home who are being deprived of adequate preliteracy training from ages 2-4 for a fraction of the cost of any standard school model. Thus there is a high probability that legislatures will fund a new type of public education that is Internet based to supplement and enhance the standard system.

Waterford believes that schools will ultimately decide to accelerate the acceptance of software rather than risk losing the support of the parents and their tax base. They will also likely try to offload part of their instructional load to the home where there is more time available to work on technology than at school which is only open for 180 days a year (less than half of the days in a year) and runs for just six hours a day of the 16 waking hours available in most homes.

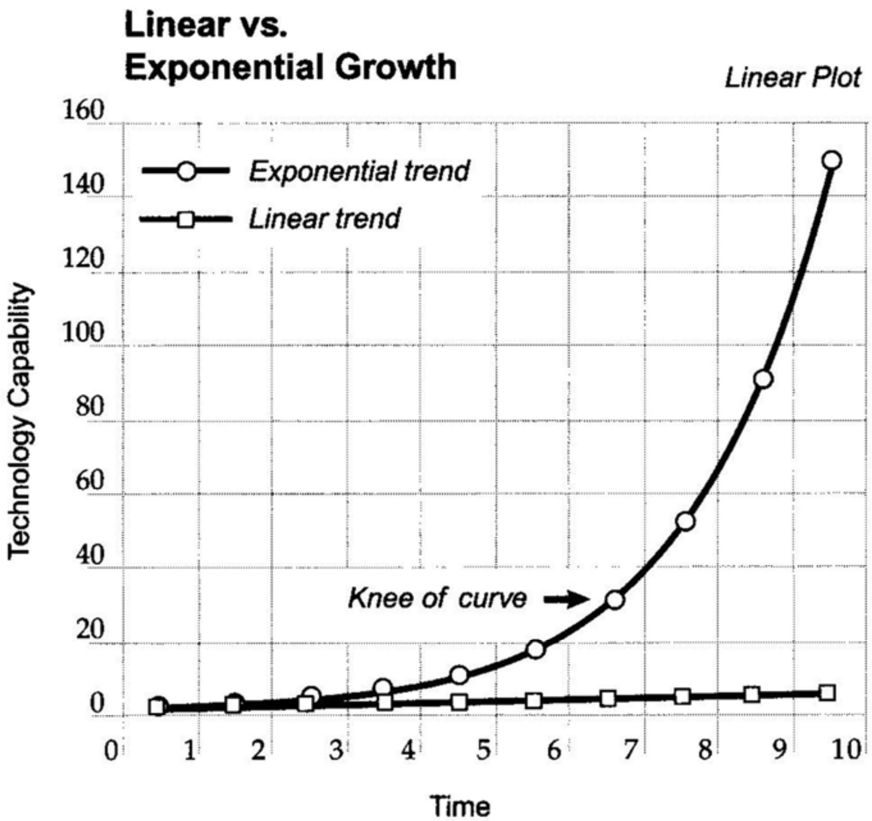
Christensen's greatest contribution is that he alone with Romer among business theorists understands the importance and necessity of investing in **educational software** because it is the interface and21 conduit that allows us to harness the accelerating hardware energy that is at the core of his disruptive strategy. Only software will help us solve the greatest educational problem we face: how do we economically develop the ability to provide customized, individualized instruction to all children to prepare them for a knowledge-based economy and world?

He recognizes that only software can provide the solution by providing enough work to offer instruction with stunning precision for precisely the need of the child at that time in a a manner that his or her brain is wired to understand, and this is one of the most powerful insights in the history of education. Almost every other educational theorist is enamored with making some aspect of the standard model more efficient. Such approaches do not work and cannot work because they fail to provide enough work to the delivery system which requires exponentially more work to customize instruction for the child.

His other great contribution is his unlocking the **concept of "disruption"** and the laws and forces that surround evolving technologies. This understanding helps us innovate and improve our organizations as we work with these technologies and prescribe approaches that are predictable because Christensen has outlined the underlying processes that control them. This knowledge helps us understand, utilize, and benefit from these forces instead of being buffeted by them because of a lack of comprehension.

Ray Kurzweil

The technology entrepreneur and writer Ray Kurzweil has the finest grasp of the **accelerating evolution of power** from technology of any of the current writers. He also understands the power of doubling over time as it offers exponential growth compared to the traditional linear percentages that we are accustomed to in viewing growth trends. This curve is particularly useful in understanding the implications of Moore's law which explains the unique growth characteristics of the microcomputer industry where the power and storage of computers are doubling without additional cost every two years. Thus what appears to be a simple arithmetic process where a quantity is simply doubled over some time period, is really the unlocking of an exponential process of stunning power. In other words, as the exponential trend displays below, we are entering a period where schools and homes will have access to undreamed of inexpensive resources to help educate children at a customized and individualized level that will maximize their educational opportunities.



Linear versus exponential: **Linear growth is steady; exponential growth becomes explosive.**

Kurzweil has also does some excellent analysis in applying the implications of the doubling energy curve to a **calendar of predictions** about what this exponentiation will mean to our civilization in the decades and centuries ahead.

Norbert Wiener of MIT (1894-1964) and the Concept of "Feedback"

One of the most profound breakthroughs in cognitive analysis and artificial intelligence that will improve our ability to educate our children with the new software has been documented by M. Mitchell Waldrop in his remarkable history of the development of the personal computer, *The Dream Machine*. In his book he explains how teams of scientists labored in the 1930s to solve the technical problem of how to shoot down an enemy plane from the ground with antiaircraft fire when there are too many variables to handle such as airspeed of the aircraft, its maneuvering patterns, the temperature of the gun barrel, wind speed and direction, the temperature and viscosity of the grease on the swiveling platform, the presence or absence of sand or other pollutants in the grease, the skill of the gun crew, etc. This was a desperate problem that needed to be solved to help England protect itself during the blitz. Sending their children from their cities to the country to protect them did little to solve the military problem.

> All across the southern tier of England, the speedy new warplanes of the Luftwaffe were proving entirely too agile for the artillery on the ground. The English gunners simply could not react fast enough to the German pilots' twists and turns; too many of their shells were hitting empty air. And the consequences of that failure were being felt every night in central London.
>
> The obvious solution was some kind of high-speed electronic fire-control system, one that would take in radar data and then automatically give the gunners a pointing vector. The obvious problem, unfortunately, was that the system would have to allow for the shells' time of flight, which meant extrapolating the enemy pilot's trajectory at least a short time into the future- including all those random twists and turns.

In his book *Grammatical Man, Information, Entropy, Language, and Life,* Jeremy Campbell notes that "It was estimated that more than 10,000 rounds of ammunition were fired from three-inch antiaircraft guns for every enemy plane shot down over London," and "since the target moved across the sky about as fast as the shell could travel from the antiaircraft gun, the crews needed to aim ahead by as much as thirty lengths of the plane."

Norbert Wiener of MIT was one of the scientists working for the government on the problem, and as a mathematician he recognized that he was facing a problem of statistical probability that with the help of the speed of light in the form of a new invention called radar he might solve by developing the ability to continually adjust the fire control system with **feedback** loops based on real time information from the radar. Thus controlling the gun would require constant feedback to establish where it is in relation to the ideal, and then apply a new set of commands to redirect its position.

That the principles of feedback worked became clear a few years later according to Campbell when "The American-designed electrical predictor for antiaircraft guns went into service on the east coast of England in August 1944, less than two months after the first wave of German buzz-bombs appeared in the sky. They brought about a startling improvement in accuracy. Before they were installed, only 10 percent of pilotless V-1's were shot down by ground fire. Afterward, 50 percent were destroyed."

From the standpoint of education, Wiener is a giant who has provided us with models on how to use technology in man-machine relationships that will maximize our ability to teach children wisely and well in an environment fraught with confusion, noise, raging hormones, conflicting agendas, political strife, and adolescent confusion. His development of cybernetic theory, with its key components of prediction, information, feedback, and adjustment running in a continuous cycle, is designed to handle the random inefficiencies of a standard school setting. We know from his concepts and mathematical theory that if we follow his model, we can be successful in our difficult effort to produce excellence in a setting fraught with disorder and confusion (entropy). This master model helps focus on the most efficient possible algorithm to produce the greatest possible success.

A second contribution he offers is a **man-machine model** which authenticates the validity of using technology to solve some of our greatest **human** problems. Indeed he not only authenticates the value of technology, but demonstrates the **necessity** for the use of technology to solve certain human problems. The book that spells out these ideas is entitled *The Human Use of Human Beings, Cybernetics and Society***,** a title that suggests his belief that there is the possibility of using machines to offer enormous benefits to human activities. What he demonstrates with cybernetics is a way of linking to an accelerating surge of energy that is available through harnessing the potential of electricity in machines that can provide and comprehend feedback and computation.

His insights on the value and function of feedback have hitherto had little impact on educational theory because they only have meaning in a setting where the speed of light is available to calculate the status of the goals being implemented. The use of radar provided this capability in fire control systems, and now that we have the microprocessor available, we will be able to offer this capability to education once the necessary software programs are developed. Then just as the scientists used the speed of radar to measure the trajectory of both the aircraft and the fired shell to provide constant ongoing adjustments based on real time feedback, so our scholars will use the speed of light to measure the learning trajectories.

Our trajectories in schools are children, teachers, and classes, and we will be substituting computers and networks for radar, but Wiener's brilliant techniques will provide the solution for a manual system that is inherently full of imperfections. This will free us from our relentless quest to fine tune the perfect teaching moment and supplement the drive for perfection of presentation with a method that can correct for less than ideal utterances from an exhausted teacher. Or similarly, this cybernetic approach will help compensate for less than perfect attendance or attention from a student who may be thinking of something else at the scheduled learning moment, or even be absent at home with the flu. We badly need this system that will allow us to live with the realities of a school and help us track and adjust to what **is** instead of what **should** be. Knowing what is needed and being able to provide it will be the new frontier for education and the heritage of Wiener's work. Thus he has shown us both **how** to accomplish it and the **need for technology** to accomplish it both in school and home settings.

A third contribution from Wiener is the impact he had on the field of artificial intelligence. Even a lowly thermostat is exhibiting a form of intelligence as it decides based on feedback when to turn the system on or off. From the standpoint of education, this means that his cybernetic approach has given us the ability to have the computer gradually improve the quality of the instructional and management programs as we learn how to give them additional intelligence and teach them how to improve themselves. Adjustments made as a result of feedback on student performance will increasingly be able to provide guiding intelligence in real time. With a machine running at trillions of instructions a second with almost unlimited storage, the depth of information that can be stored, accessed and used to guide a unique instructional path for any student will be priceless. The potential for instantaneous and continuous feedback will allow positive instructional outcomes for each child while providing parents and teachers with information and help.

Alvin and Heidi Toffler: Combining the Internet and the Computer at Home

The Tofflers are excellent futurists who have written a number of books describing the most important trends in society, science, business, and education. They have been very helpful to political and business leaders in helping them understand what is coming in society and clarifying what the most productive approaches will be given the new emerging realities of the future, or what they call the “deep fundamentals” in their new book *Revolutionary Wealth.* The three deep fundamentals that are generating a new wealth system are driven by “dramatic changes in our relationships” with **time**, **space**, and **knowledge**, all of which will be improved by having the Internet connecting microcomputers in every possible location. Once this occurs, the barriers of time and space/place are minimized. **Having access to information anytime or anyplace is truly revolutionary.**

They note that industrialization developed a factory system requiring workers to leave their homes and work in factories where the expensive machines resided, and that schools adopted a similar factory model where sharing the expensive expertise of teachers required students to leave home each school day to have access to this expertise.

But as the cost for computers and the Internet continues to decline while speed and storage increase, the home will be empowered again to be an alternate center of work and education for both parents and children. “Education remains locked in the classroom, but, paralleling work, is likely to migrate at least partially back into the home and to other locations as Internet access, WiFi and cellular communications spread through society.”

Their points about the importance of knowledge in a knowledge-based society are well taken, but they also stress, as Romer, Heckman and Hanushek do, that a nation that concentrates on educating its citizens not only prospers because of their employability, but also because knowledge is unlike other resources in that it does not get used up. It actually expands as it is shared, and the price does not go up because of scarcity. It inevitably spreads to benefit all the citizens in a society as trained minds invent and develop new capabilities for using the earth’s resources wisely and well. According to the Tofflers, “Arithmetic doesn’t get used up when we apply it!” as contrasted to many of our other natural resources; in fact it actually grows and compounds in society’s favor as we use it in our daily commerce.

Waterford believes that the Tofflers’ insights about the revolutionary impact that the computer and the Internet will have on the deep fundamentals of time, space (place), and knowledge, particularly in the re-empowering of the home, offer us a magnificent overview of the coming revolution in education and its potential to help provide educational equity and excellence for children all over the world.

The Impact of Journalistic Pundits

As I have toured the input of scholars, I have also found that we must not forget the contributions of the fourth estate, our journalists, reporters, and writers. They are contributing in a cybernetic fashion by providing us with constant informed feedback about society's assumptions, trends, status, and ideals while recommending concepts and people for our consideration amidst the noise and babble of everyday existence. For example, note the talent and impact of such writers as Brooks, and Friedman from the *New York Times* who consistently provide fresh insights for their readers, no matter what their party affiliations or beliefs. In fact as we have seen in his insights about Paul David, even the politically biased reporting of Krugman can occasionally be helpful. For example Friedman's book *The World is Flat* has helped the world understand the implications of the Internet and its impact on the world labor markets.

He has alerted us to the successful use of the speed of light in allowing nations and populations to communicate and transfer information inexpensively and noted how this has demolished many traditional trade barriers and will cause severe labor problems to nations that are unable to educate their citizens. His thoughtful analysis suggests there are ten forces that have been unleashed between 1989 and 2000 by the new technologies that are flattening the world's traditional barriers between nations. One of the by-products of harnessing the speed of light is that three billion new competitive workers were suddenly produced from India, China, Eastern Europe, Latin America, Central Asia, and Russia at about the year 2000, and the existence of these workers has changed forever the rules that will govern commerce and education.

In a column in the *New York Times* on August 3, 2005, entitled "Calling All Luddites," Friedman succinctly sums up our technological challenge:

> The world is moving to an Internet-based platform for commerce, education, innovation, and entertainment. Wealth and productivity will go to those companies or countries that get more of their innovators, educators,

students, workers and suppliers connected to this platform via computers, phones and P.D.A.'s.

The Waterford Institute: Energy and Work: From Approximation to Precision

The Waterford Institute believes that Hanushek's desire to identify what works from a scientific point in improving education is a critical one, but the solution will come not primarily from developing more accurate instructional algorithms, but first from harnessing the power and energy of the new emerging technologies. The new technologies will flood the educational delivery system with inexpensive sources of energy and work that can be used both to aid the manual workers (teachers, parents, and students) in the delivery of individualized interactive instruction and simultaneously help researchers in their quest to develop more accurate instructional strategies based on the latest research. This new energy will provide an "educational revolution" equivalent in power and influence to the "Industrial Revolution" and have just as positive an economic impact on those countries that implement them as the Industrial Revolution did.

Fortunately economists understand the power of technology, and they will be helpful in proselytizing its virtues to a world that is often ambivalent about frontal discussions of energy, power, and technology in human affairs.

Perhaps **the key insight needed for the public** is the recognition that if there is only a modest amount of limited energy available to support the manual labor of the teachers, parents, and students, then the teachers and schools can only **approximate** an educational solution for the group. The approximate solution currently available is enough for students who are bright (even though they might be bored), but **not** for the population as a whole that needs to develop its talents both for economic and humane reasons. Whenever possible our culture needs enough energy to guide it beyond approximate approaches to ones that offer precise solutions. **Educational wisdom begins with this insight!**

If we examine the root of our educational problem, we find once again that energy limits are restricting our ability to understand, control, and utilize optimal educational processes. We need energy to accomplish useful and applicable work, and our ability to deliver and understand education is limited to the amount of work we can harness to serve in our quest. In general, education is still a manual profession, and manual professions are not noted for their ability to generate extraordinary amounts of measurable work. Unlike horses that have a work measure assigned to them called a "horsepower," humans have never developed a unit of work called a "personpower" or "humanpower." And if we did, we would be demoralized by the modest physical limits of the energy we can generate. Our greatness as a species is determined by our capacity to think and innovate, by our intelligence and knowledge, and not by our physical prowess.

As a poet says, "man may be the measure of all things," but sensible humans will always harness technology to help them transcend their human limitations. Yes, we can walk manually, but where possible we will extend our range by riding a bike, taking a bus, subway, train or plane, or driving a car. Similarly, when trying to communicate, we can talk directly to someone or use technology to extend the range of our audience by writing letters, writing an article or book, sending a telegram, calling on the phone, sending an email, talking on the radio in an interview, or using television to communicate with as many people as possible.

But when teaching, the only option the teacher has to augment his lesson to the students is to refer the students to the stored work of others in books and articles. Unfortunately we have never developed technologies to help us in our teaching tasks beyond using paper, pencils and pens, blackboards, whiteboards, overhead projectors, and books; none of which can actually interact with the child. They are passive sources of information and unable to provide corrective feedback.

Think of the inefficiencies involved in teaching compared to using technologies. It takes over twenty years of preparation before a human is ready to teach, and, once launched, the teacher is only available to teach his or her students for about 12% of a year (about 1,080 hours of the 8,760 available). Contrast the human limitations with the use of technologies which are available 100% of the year and have no other duties involving families, children, food, sleep, friendship, commuting, sports, job instability, mental and health problems, laundry, etc.

Because the **standard school model** (which most cultures have adopted) has a limited amount of work available in the system, schools are forced to operate in a **quagmire of approximation.** This compromises their ability to offer educational excellence because this standard model can only approximate an ideal instructional sequence for each child. This forced strategy of approximation leaves the individual needs of many students unmet, and until technology is introduced to add work to the system, the standard model will be unable to produce more than a rough approximation of excellent teaching and curriculum.

The **standard model** is the educational approach that most of the educated world has evolved (in a Darwinian sense) into adopting after centuries of experimentation. It generally includes a teacher, a building to house the school, classrooms with 15 to 50 students, some books, blackboards or whiteboards and assorted technologies from chalk to computers depending upon the economic level of the population. The students are assigned a grade level by age. They first matriculate in school when the month of their birthday matches an arbitrary schedule published by the local school district (e.g. all children who turn 5 before November 30th will begin kindergarten this fall when school opens in September) no matter what the status of their preparation might be. The system they enter usually has a set curriculum, some administrators, and a governing board in addition to teachers, books, and physical plant. In a country such as America approximately seven percent of The Gross National Product is allocated to education, and given the accelerating needs of competing sectors such as health care and national security, there is little chance that this percentage is likely to rise significantly.

And even if more money were allocated, this would add little to the power of the standard model because education is an **old and mature delivery system** restricted for the most part to using manual labor. Adding money to a mature delivery system does little to improve it unless it introduces new technologies into the system that can generate significantly more work for the tasks of the system. In order to clarify how additional work will help improve education, we first must understand how **work limitations force approximation into a delivery system.**

In the military delivery system we can study a similar phenomenon where the addition of work improves the effectiveness of the delivery system by moving it from approximation to precision. Armies have moved from throwing rocks in the general direction of their opponents to sophisticated weaponry that can hit a target at a considerable distance with sniper fire, artillery shells, and guided missiles. In the First World War pilots threw bombs manually over the side of the aircraft, in the Second

World War the US used the Norden Bomb Sight with mixed results from carefully locked-in bomb runs at a fixed altitude, and in the War in Afghanistan and Iraq, we used intelligent bombs that found their targets with astonishing precision through the use of sophisticated technologies. In these cases **additional work added to the system by technology provides added precision to the tasks of the delivery system.**

There are many obvious shortcomings in the standard educational model which forces us to teach by approximation. For example, as noted earlier in this document, when we sort students into classes by age, inevitably there is a large spread in student ability in a class which forces the teacher to teach the subject at a level that is only appropriate for certain students in the class. While this teaching by approximation works reasonably well for the average student, it does leave some in terror and shame who find the pace too rapid and others languishing in boredom, frustration, and anger who find the pace too slow. What would be far more helpful for the students would be to have the materials presented to them precisely at the level and pace of their individual needs.

The work limits of the standard model provide even more profound challenges for children who suffer from a variety of learning disorders. For example, a child who is learning to read may have a severe case of dyslexia which is stopping him or her from succeeding. In many cases the prognosis is grim for this child because the teacher lacks the expertise and time to provide specific help for the child to insure mastery, and the support offered by remedial specialists and tutors is frequently ineffectual.

Even when I ran one of the best private schools in the country in New York City, I discovered that many children had learning difficulties that no one on my staff could understand because learning is not yet a science. We would offer tutoring by specialists who themselves only dimly understood what was going on in the child's mind, and when this failed, the parents were forced to troop their children around the city to specialists and clinics that were emphasizing a particular approach that might or might not help.

We are witnessing the same phenomenon at our research school in Utah which has over 1,000 children from preschool through high school. Children are carefully tested before being accepted, the teachers are very talented, the setting is magnificent, the class size is reasonable, the children are mostly drawn from the highest SES and are taught by specialists in science, music, dance, and the arts in addition to their homeroom teachers.

Despite all of this support, the school administration has learned from careful testing of the students to expect that in our lower school population of about 400 students in grades K-5, over 60 children require personal tutoring. The numbers vary from year to year, but at least 15%, or about one child in seven needs tutoring to overcome reading difficulties.

If Waterford is experiencing this ratio in optimal circumstances where children have been tested before being accepted, imagine the number of children that should be receiving additional individual instruction in public school environments no student is denied admission or services. Some excellent research has been conducted by the National Institute of Health (NIH) to determine the number of children who need tutoring, and they report that at least 1 in 5 (20%) should have it because of the way their brains are wired (dyslexia) or because of the lack of preliteracy training in their background.

As the Institute and school came to terms with this startling and unexpected need for additional individualization in such an optimal setting, our software developers produced a remediation program to support the manual tutoring efforts of the faculty and staff.. After implementing the program, the school had only two students who needed tutoring after their kindergarten year rather than the twelve that were traditional. This software-based tutoring program is the first multisensory computer based tutoring program that has been developed to support the efforts of school tutors. Most of the successful manual tutoring programs such as Orton-Gillingham, Lindamood Bell, or Wilson use a multisensory approach which enables the child's brain to be stimulated by alternative sensory approaches that help activate those areas of the brain that have not been functioning optimally for the learning task at hand. These areas must become activated in order to produce a fluid reader.

Special testing software has also been developed with sophisticated computer diagnostic programs in reading that will automatically identify these children far earlier and more accurately than we currently can. This software is allowing us to increase expert individualization for the students while avoiding the expense of our current policy which requires additional manual labor from resident experts. This is particularly helpful in identifying the potential problems of young children who have not learned to read well enough to take standardized paper tests and require one-on-one oral testing by an adult.

In public schools the situation is even more difficult because the teachers will have a number of students whose parents failed to provide any work in pre-literacy training before the child entered kindergarten or first grade. The teacher may sense that many of the children need extra help in some basic areas (such as achieving automaticity of the alphabet, understanding print concepts, or mastering phonemic awareness), but for the most part there is little that he or she can do to help because there are other students in the class influencing the pace of the class. Here enforced instructional approximation will be devastating to the slower cohort who needs extra instructional time that the system cannot provide. Because of energy and work limitations, the teacher has no option except to progress at a pace that is appropriate to the class as a whole while watching the slower members fall behind, mortified by their sense of failure, and the brighter members grow bored by the absence of challenges.

The Erosion of the Educational Barriers under the Onslaught of Technology

Fortunately the most exciting and hopeful innovation in the history of education is entering the playing field as the new technologies such as the laser, fiber optics, the Internet and microcomputers become available. They will flatten the barriers of the educational delivery system that have kept so many children from having access to educational excellence. Similar to the historical cases cited earlier in this paper involving technological improvements of other delivery systems, we now have a dramatic new energy source available to allow significant breakthroughs in the educational delivery system. The manual educational delivery system is about to receive staggering energy boosts that will forever change our educational strategies and effectiveness; In the next few decades we will be approaching the potential to give all children access to both equity and excellence to the extent their governments allow it.

Access to extraordinary educational instruction will become very simple because it will be available very inexpensively (less than $500 a person a year and continuing to decline) in homes, schools, community centers, and religious centers such as churches and synagogues. Using the Internet some governments will make the educational software available to their citizens without cost to them, and at very little cost to the government. Since the microcomputers are improving (without cost) in power and storage, the new emerging energy and work capabilities will provide innovative instructional approaches that we cannot yet even conceptualize.

Waterford has identified at least 14 barriers to reform that schools unconsciously have erected, and these will gradually be eroded by the contributions from technology. For example as this paper has noted, children only have access to instruction a small percent of the **time** and have to travel to a specific **place** where the system is **work deprived** and forces manual teachers to teach primarily to groups by approximation. Just thinking about these three barriers of time, place, and work helps to clarify how difficult it is to improve the current system, not to mention the complexity of the remaining 11 barriers such as the quality of the teacher training, the way textbooks are chosen, the inability to scale excellence, the lack of understanding of the importance of computer usage, the quality of the curriculum, the incentives that drive vendor sales, and, most frustratingly, the inability to recognize and retain an understanding of the contribution that the technology is offering.

With surprising frequency the administration, teachers, and school community miss the positive impact the technology is having on the students as it is introduced and gradually revert back to standard teaching practices. One of the hardest problems for the technology supporters to face is the frustration of producing outstanding academic results with their program and then have to come to terms with the devastating discovery that the teachers and administrators fail to notice the data and either drift back to the habitually familiar, or get distracted by new reforms. In one case, a carefully organized study demonstrated extraordinary gains in a school. The year before the computers and software were installed, the kindergarten children finished the year in the 50th percentile with the children in the lower third scoring in the 16th percentile. The next year after using the technology, the class as a whole scored in the 92nd percentile and the lower third was in the 87th percentile.

Despite these astonishing gains, the next school year the teachers did not bother to turn the computers on for the first few weeks as they reverted to their familiar teaching approaches. Waterford had to push them to resume the use of the computers. Old habits die hard, however, and within two years the computers were no longer being used in an organized manner. There was no institutional understanding or memory ready to comprehend the contribution the computers offered, and gradually the inertia of the familiar manual teaching approach took over and the hardware was silenced. This is one of the problems Paul David identified when he noted it usually took institutions about 40 years to accept the full potential of new technologies.

In another school which had been at the bottom of its district, the skillful use of the program driven by a talented aide resulted in the school going from the bottom to the top of the district in reading which produced two fascinating responses: First the district was irritated by the loss of extra funding to the school because of its success. Secondly the district's immediate response was not to expand the program to its other schools, but to transfer the equipment to another school that was in trouble, not understanding that the if the school were deprived of the hardware and software, its scores would again collapse.

Another district which purchased the hardware and software for thousands of classrooms failed to allow time to be available for the children to use the program because the administrators scheduled a mandatory 90 minutes a day for a textbook based reading program at the same time. Later they ignored the data from a few schools that had managed to sneak enough time (15 to 30 minutes a day) and had their scores soar. The district evaluators later assured the board and the press that the program was a failure without recognizing their scheduling policy had doomed the program since the children were not allowed the time on the terminals.

In another state that had a foundation fund the materials for every kindergarten class in the state, the children in the lower third of the reading scores who used the program properly ended up with the highest gain ever recorded for as large a cohort, but both the sponsors and leadership missed the implications of the study and moved on to other reforms.

These examples are meant to clarify the problems that schools face and not to condemn them. These are the realities of the profession, and they deserve our attention and respect in order to help solve them. The reader should understand that this discussion is not an indictment of schools, but a reflection on the current state of affairs in the school community which will require time to transition from a manual teaching tradition that is over 500 years old to one that feels comfortable with technology. This will happen over time as the software becomes more effective, the hardware drops in cost and improves in performance, and a new generation of teachers, students, and administrators emerges that is comfortable and enthusiastic about using technology. In this new atmosphere they will be receptive to understanding the contributions the technology is offering, and indeed, will find ultimately they are unable to perform without it.

What Have We Learned?

Historians, scientists, mathematicians, economists, philosophers, scholars, writers, pundits, and common sense suggest there is a great season of hope coming to global education because of the unleashing of a surge of energy from the new technologies. Once the software is developed and new educational traditions are established in homes, schools and other centers, students will have access to educational excellence. This access will contribute to global economic progress and the ability for more of its citizens to live meaningful lives. Paraphrasing a number of economists, "Nothing will be more important for global progress than this." This will evolve for the following reasons:

(1) The new technologies will increasingly capture more of the speed and energy of light as Moore's law and scientific ingenuity continue to evolve over the coming decades. The improvements to the speed, storage and connectivity of microcomputers will continue to grow without additional cost to the user at 1% a week which effectively provides a free doubling of available computational energy and storage every two years.

(2) As this paper argues, once an explosive surge of new energy exists for a given delivery system, the culture gains extraordinary economic advantages as the additional energy is implemented. These advantages preempt the traditions of the older delivery system, particularly if that system is driven primarily by manual labor. Fortunately as the delivery system is modified to handle the new technologies, new jobs are created that pay higher salaries because they require higher skills. But a knowledge-based society requires its citizens to be well educated, and since educational excellence has traditionally been more available

to the wealthy than to the poor, there is the danger of accelerating class differences unless technology is introduced to insure both equity and excellence for all citizens.

(3) The consequences of this education revolution will be profoundly positive because it will expand the nature of the educational delivery system from a school and campus centered approach to one that adds additional educational locations and (in particular) the home. Eventually excellent individualized, interactive, artistically compelling education will become an **inexpensive commodity** instead of the expensive luxury it is today where access to the best schools is skewed toward those with a high SES or natural brilliance which can generate scholarships. And most importantly it will spread its potential to the home much as music has.

(4) Economists and cognitive scientists have shown that the best time to begin to invest in children's cognitive education is between age 2 and 3. This suggests that having the technology available over the Internet to the home will provide the maximum impact because there will be additional time available in home settings for the younger children. This will help the children by training their **cognitive skills** and help mitigate the damage to the children's **social skills** that too much early exposure to a preschool setting generates for some students in comparison to their peers who stay at home with their families.

(5) The importance of the preschool years is becoming evident as economists such as Heckman have analyzed the financial implications of starting children's educational experiences earlier than Kindergarten. Other scholars have noted data such as the government's Early Childhood Longitudinal Study that discovered that by the time the children start Kindergarten there is already a devastating difference between the students from the high SES families and those from the low SES population. The work of Hart and Risley, Marilyn Adams, and Robert Sampson adds additional important data stressing the consequences of not addressing the lack of preliteracy training in the homes of children in economically deprived families.

(6) One of the most hopeful signs of the coming technological revolution will be the affordability of the materials and hence the dramatic increase in access to educational excellence. For example, the price of Head Start (age 4) and Early Head Start (age 3) is at least $7,000-$9500 a head for the 900,000+ preschoolers in the program. For an additional $400 to $475 per student (currently), and much less over time, the students could receive at-home instruction in reading, math, and science over the Internet for less than 7% of the preschool costs. In addition, many children who do not have access to Head Start could have access to instruction at home. The strength of these materials is in their ability to train cognitive skills, the one area where Head Start has not performed as well as hoped.

Because of the popularity of preschool programs, legislatures will gradually introduce universal preschool throughout all of our states while also gradually making the inexpensive software available both to families whether in preschool or not. Since the software, computers, and Internet will only cost a tiny percent of what a preschool does, the governments will make it part of their preschool program offerings.

(7) All the variables are in position to harness the surge in energy available from the new technologies except that the software offerings that determine the instructional effectiveness of the ever-improving hardware are a bit thin in some areas because the development costs are greater than most organizations can afford. For example, Waterford has spent over $115,000,000 in developing the computer software for teaching reading, math, and science for just grades K-2. The Institute was able to accomplish this with support from foundations, individuals and royalty payments for the use of its software, but it took the organization over fifteen years to accomplish this.

There will be two sources of capital needed to produce a healthy sustaining educational software market. **First,** money is needed to develop **disruptive** software that can offer inexpensive, convenient programs that will serve new users at home and in school in specialty areas such as languages, music, art, simple educational games, or remediation. These can be built with modest amounts of capital, and some of them may be successful enough to initiate a disruptive cycle that will impact larger traditional organizations serving these markets. The software may make contributions to schools, but it will not threaten the existence of these quasi-monopolies as they might if schools were subject to traditional market disciplines.

Second, there will be much more expensive software built that is **full-service software** because it will be powerful enough to offer programs that are much more customized for each child than the standard school model can provide. This individualization will be offered at a fraction of the cost-per-child compared to standard school models. However, the difference in cost to develop the software between the two is considerable. The **disruptive** products will cost hundreds of thousands to develop while the **full service** products will require tens of millions.

Once the full-service software has been developed, then the schools will begin to adjust and adapt the software as part of their program. Since most parents want their children educated by live people, they will still support the schools, but they will expect the schools to offer a superior product by incorporating the benefits of the new software **in conjunction with** teachers.

Those who have an interest in seeing that the software potential is developed and implemented can help to accelerate the process by providing funds for either the disruptive or the full service approach. **The public schools will not complete their acceptance of technology until the full service software is available.**

(8) In order to service the millions of people worldwide who will be logging in to the educational software on the Internet, massive file servers will need to be built by Waterford and others to serve their users. The resulting databases will offer an opportunity to conduct research on the effectiveness of different educational strategies, and slowly a new science of education will emerge. Hanushek's frustration in not being able to measure the most effective educational strategies will be addressed and solved. Imagine running blind controls on a few million

students a day and receiving the results in real time. A researcher's paradise is on the way.

(9) Above all else, we can learn from history the impact that new energy sources will have on education. We can also see that there are a number of new inexpensive energy sources using ever increasing amounts of the speed of light as the technology evolves that schools can use. Using Paul David's rule of thumb that suggests that there is usually a 40-year delay between the introduction of a new technology (such as the dynamo or the computer) and its productive acceptance by the older delivery systems, we can be encouraged because schools have been experimenting with the computer technologies for about 30 years and are slowly moving into position to use them wisely and well.

Also, as Christensen's disruptive strategies are implemented by offering software over the Internet to new groups of users such as children in the home, we can see that in parallel with the school, the home will suddenly be empowered to have access to world class instruction. And thus for the first time in history we can summon a ray of **hope** that we might offer both equity and excellence in education for the world's children.

Remember, of all the approaches that civilization has generated the only one that can sustain both equity and excellence over time is the use of technology because all who have access to it receive the same benefit, no matter how rich or poor. This is not true when access is limited to human experts because their cost is determined by market forces. Their price goes up because of scarcity. Excellence becomes synonymous with elitism, and only the wealthier, the most politically connected or the most talented are allowed access, be it to great public or private schools, colleges, doctors, jobs, architects, tutors, theater productions, etc.

Here is the genius of technology! Everyone sees the same movie, the same TV program, or reads the same version of a book. My movie is not grainy, scratched and black and white if I am poor while yours is in color. We both see the same movie or production, but we may not both have the same excellence available in our schools. Someday we will all have inexpensive access to ideal instruction using the newest learning theory and customized to fit our individual learning styles. It will be presented in color using magnificent 3D animations, music, art, and teaching techniques that adapt to our individual learning profile.

Hope is a wonderful thing! After decades of hard work by many caring people without significant measurable returns, the new energy sources will reinvigorate us and certify the validity of our dreams and educational hopes for all of our children.

The International Educational Revolution on the Horizon

The education technology revolution will take a number of forms, all of which happily are compounding in favor of children. Above all else the revolution will provide convenient access to education any place and at any time for almost no cost. The barriers that have limited great education to a privileged few will suddenly disappear in the technologically advanced societies and then gradually spread throughout the globe as the speed and energy of light and electricity become available over the Internet on very inexpensive hardware. As societies recognize the educational and economic benefits for their young children, they will gradually find the resources to insure the presence of the Internet and all of the capabilities it represents.

Once the Internet is available everywhere, any individual will ultimately have the ability to gain access to very inexpensive and powerful instruction in literacy, reading, science, and math no matter how poor the local schools might be. Although there will be the danger that the educational potential of the Internet may be misused by those cultures that have a vested interest in providing a biased education to their children, the economic consequences of such a path and the interest of parents in providing their children with the best education possible will probably keep this to a minimum. Equity and excellence will be the norm, and as a result, ultimately most people on the globe will have their personal potential unleashed.

In his book *The Wealth of Nations* (1776) Adam Smith taught us the power of trade as it links and harnesses the energy of many people working to provide goods and services to one another. Trade optimizes the number of potential customers available to a producer. The power of number can be quickly demonstrated by watching a school ritual where a tug of war is scheduled between the large and powerful teachers against the youngest students who seem frail, puny, and powerless by contrast. Because of the energy available to the many (students) over the few (faculty), the many always defeat the few to the spontaneous joy of the children. We could use some spontaneous joy in education, and we will have it as we build powerful new software using the speed and energy of light on our newest technologies and unleash the most important energy in the world: the potential of the human mind.

And as Adam Smith observes, our linkage to all children on the globe at the speed of light will accumulate the maximum possible educational productivity and benefit. We owe this to our children and, of course, to ourselves. How lovely to be part of such a wonderful era for children!