

The Law of Accelerating Returns
by [Ray Kurzweil](#)

An analysis of the history of technology shows that technological change is exponential, contrary to the common-sense "intuitive linear" view. So we won't experience 100 years of progress in the 21st century -- it will be more like 20,000 years of progress (at today's rate). The "returns," such as chip speed and cost-effectiveness, also increase exponentially. There's even exponential growth in the rate of exponential growth. Within a few decades, machine intelligence will surpass human intelligence, leading to The Singularity -- technological change so rapid and profound it represents a rupture in the fabric of human history. The implications include the merger of biological and nonbiological intelligence, immortal software-based humans, and ultra-high levels of intelligence that expand outward in the universe at the speed of light.

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You will get \$40 trillion just by reading this essay and understanding what it says. For complete details, see below. (It's true that authors will do just about anything to keep your attention, but I'm serious about this statement. Until I return to a further explanation, however, do read the first sentence of this paragraph carefully.)

Now back to the [future](#): it's widely misunderstood. Our forebears expected the [future](#) to be pretty much like their present, which had been pretty much like their past. Although [exponential trends](#) did exist a thousand years ago, they were at that very early stage where an [exponential trend](#) is so flat that it looks like no trend at all. So their lack of expectations was largely fulfilled. Today, in accordance with the common [wisdom](#), everyone expects continuous technological [progress](#) and the social repercussions that follow. But the [future](#) will be far more surprising than most observers realize: few have truly internalized the implications of the fact that the rate of change itself is accelerating.

The Intuitive Linear View versus the Historical Exponential View

Most long range forecasts of technical feasibility in [future time](#) periods dramatically underestimate the power of [future technology](#) because they are based on what I call the "intuitive [linear](#)" view of technological [progress](#) rather than the "[historical exponential view](#)." To express this another way, it is not the case that we will [experience](#) a hundred years of [progress](#) in the twenty-first century; rather we will witness on the [order](#) of twenty thousand years of [progress](#) (at *today's* rate of [progress](#), that is).

This disparity in outlook comes up frequently in a variety of [contexts](#), for example, the discussion of the ethical issues that [Bill Joy](#) raised in his controversial [WIRED](#) cover story, [Why The Future Doesn't Need Us](#). Bill and I have been frequently paired in a variety of venues as pessimist and optimist respectively. Although I'm expected to criticize Bill's position, and indeed I do take issue with his prescription of [relinquishment](#), I nonetheless usually end up defending Joy on the key issue of feasibility. Recently a Noble Prize winning panelist dismissed Bill's concerns, exclaiming that, "we're not going to see self-replicating nanoengineered entities for a hundred years." I pointed out that 100 years was indeed a [reasonable](#) estimate of the amount of technical [progress](#) required to achieve this particular milestone *at today's rate of [progress](#)*. But because we're doubling the rate of [progress](#) every decade, we'll see a century of [progress](#)--*at today's rate*--in only 25 calendar years.

When people think of a [future](#) period, they intuitively assume that the current rate of [progress](#) will continue for [future](#) periods. However, careful consideration of the pace of [technology](#) shows that the rate of [progress](#) is not constant, but it is [human nature](#) to adapt to the changing pace, so the intuitive view is that the pace will continue at the current rate. Even for those of us who have been around long enough to [experience](#) how the pace increases over [time](#), our unexamined [intuition](#) nonetheless provides the impression that [progress](#) changes at the rate that we have [experienced](#) recently. From the mathematician's perspective, a primary [reason](#) for this is that an exponential curve approximates a straight line when viewed for a brief duration. So even though the rate of [progress](#) in the very recent past (e.g., this past year) is far greater than it was ten years ago (let alone a hundred or a thousand years ago), our memories are nonetheless dominated by our very recent [experience](#). It is typical, therefore, that even sophisticated commentators, when considering the [future](#), extrapolate the current pace of change over the next 10 years or 100 years to determine their expectations. This is why I call this way of looking at the [future](#) the "intuitive [linear](#)" view.

But a serious assessment of the [history](#) of [technology](#) shows that technological change is exponential. In [exponential growth](#), we find that a key measurement such as [computational](#) power is multiplied by a constant factor for each unit of [time](#) (e.g., doubling every year) rather than just being added to incrementally. [Exponential growth](#) is a feature of any [evolutionary](#) process, of which [technology](#) is a primary example. One can examine the [data](#)

in different ways, on different [time](#) scales, and for a wide variety of technologies ranging from [electronic](#) to [biological](#), and the acceleration of [progress](#) and [growth](#) applies. Indeed, we find not just simple [exponential growth](#), but "double" [exponential growth](#), meaning that the rate of [exponential growth](#) is itself growing exponentially. These observations do not rely merely on an assumption of the continuation of [Moore's law](#) (i.e., the exponential shrinking of [transistor](#) sizes on an [integrated circuit](#)), but is based on a rich model of diverse technological processes. What it clearly shows is that [technology](#), particularly the pace of technological change, advances (at least) exponentially, not [linearly](#), and has been doing so since the advent of [technology](#), indeed since the advent of [evolution](#) on [Earth](#).

I emphasize this point because it is the most [important](#) failure that would-be prognosticators make in considering [future](#) trends. Most [technology](#) forecasts ignore altogether this "[historical exponential view](#)" of technological [progress](#). That is why people tend to overestimate what can be achieved in the short term (because we tend to leave out necessary details), but underestimate what can be achieved in the long term (because the [exponential growth](#) is ignored).

The [Law of Accelerating Returns](#)

We can organize these observations into what I call the [law of accelerating returns](#) as follows:

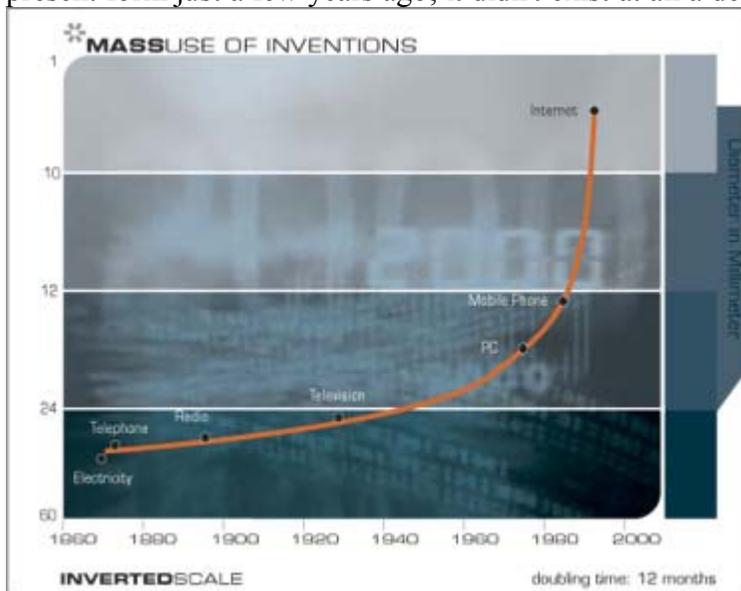
- [Evolution](#) applies positive feedback in that the more capable [methods](#) resulting from one stage of [evolutionary progress](#) are used to create the next stage. As a result, the
- rate of [progress](#) of an [evolutionary](#) process increases exponentially over [time](#). Over [time](#), the "[order](#)" of the [information](#) embedded in the [evolutionary](#) process (i.e., the measure of how well the [information](#) fits a purpose, which in [evolution](#) is survival) increases.
- A correlate of the above observation is that the "returns" of an [evolutionary](#) process (e.g., the speed, cost-effectiveness, or overall "power" of a process) increase exponentially over [time](#).
- In another positive feedback loop, as a particular [evolutionary](#) process (e.g., [computation](#)) becomes more effective (e.g., cost effective), greater resources are deployed toward the further [progress](#) of that process. This results in a second level of [exponential growth](#) (i.e., the rate of [exponential growth](#) itself grows exponentially).
- [Biological evolution](#) is one such [evolutionary](#) process.
- Technological [evolution](#) is another such [evolutionary](#) process. Indeed, the emergence of the first [technology](#) creating [species](#) resulted in the new [evolutionary](#) process of [technology](#). Therefore, technological [evolution](#) is an outgrowth of--and a continuation of--[biological evolution](#).
- A specific [paradigm](#) (a [method](#) or approach to solving a problem, e.g., shrinking [transistors](#) on an [integrated circuit](#) as an approach to making more powerful [computers](#)) provides [exponential growth](#) until the [method](#) exhausts its potential. When this happens, a [paradigm shift](#) (i.e., a fundamental change in the approach) occurs, which enables [exponential growth](#) to continue.

If we apply these principles at the highest level of [evolution](#) on [Earth](#), the first step, the creation of cells, introduced the [paradigm](#) of [biology](#). The subsequent emergence of [DNA](#) provided a [digital method](#) to record the results of [evolutionary experiments](#). Then, the [evolution](#) of a [species](#) who combined rational [thought](#) with an opposable appendage (i.e., the thumb) caused a fundamental [paradigm shift](#) from [biology](#) to [technology](#). The upcoming primary [paradigm shift](#) will be from [biological thinking](#) to a hybrid combining [biological](#) and [nonbiological thinking](#). This hybrid will include "[biologically](#) inspired" processes resulting from the [reverse engineering](#) of [biological](#) brains.

If we examine the timing of these steps, we see that the process has continuously accelerated. The [evolution](#) of [life](#) forms required billions of years for the first steps (e.g., primitive cells); later on [progress](#) accelerated. During the [Cambrian](#) explosion, major [paradigm shifts](#) took only tens of millions of years. Later on, [Humanoids](#) developed over a period of millions of years, and [Homo sapiens](#) over a period of only hundreds of thousands of years.

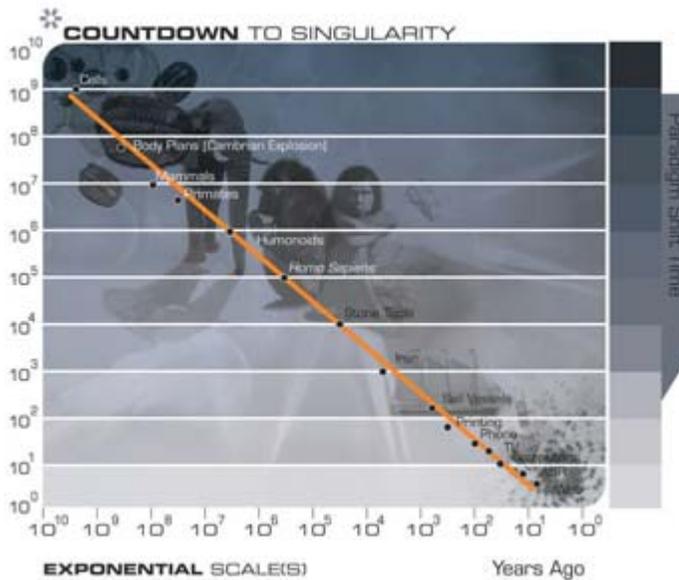
With the advent of a [technology](#)-creating [species](#), the exponential pace became too fast for [evolution](#) through [DNA](#)-guided [protein synthesis](#) and moved on to [human](#)-created [technology](#). [Technology](#) goes beyond mere tool making; it is a process of creating ever more powerful [technology](#) using the tools from the previous round of innovation. In this way, [human technology](#) is distinguished from the tool making of other [species](#). There is a record of each stage of [technology](#), and each new stage of [technology](#) builds on the [order](#) of the previous stage.

The first technological steps--sharp edges, fire, the wheel--took tens of thousands of years. For people living in this era, there was little noticeable technological change in even a thousand years. By 1000 A.D., [progress](#) was much faster and a [paradigm shift](#) required only a century or two. In the nineteenth century, we saw more technological change than in the nine centuries preceding it. Then in the first twenty years of the twentieth century, we saw more advancement than in all of the nineteenth century. Now, [paradigm shifts](#) occur in only a few years [time](#). The [World Wide Web](#) did not exist in anything like its present form just a few years ago; it didn't exist at all a decade ago.



The [paradigm shift](#) rate (i.e., the overall rate of technical [progress](#)) is currently doubling (approximately) every decade; that is, [paradigm shift](#) times are halving every decade (and the rate of acceleration is itself growing exponentially). So, the technological [progress](#) in the twenty-first century will be equivalent to what would require (in the [linear](#) view) on the [order](#) of 200 centuries. In contrast, the twentieth century saw only about 25 years of

[progress](#) (again at today's rate of [progress](#)) since we have been speeding up to current rates. So the twenty-first century will see almost a thousand times greater technological change than its predecessor.



The [Singularity](#) Is Near

To appreciate the [nature](#) and significance of the coming "[singularity](#)," it is [important](#) to ponder the [nature](#) of [exponential growth](#). Toward this end, I am fond of telling the tale of the [inventor](#) of [chess](#) and his patron, the emperor of China. In response to the emperor's offer of a reward for his new beloved game, the [inventor](#) asked for a single grain of rice on the first square, two on the second square, four on the third, and so on. The Emperor quickly granted this seemingly benign and humble request. One version of the story has the emperor going bankrupt as the 63 doublings ultimately totaled 18 million trillion grains of rice. At ten grains of rice per square inch, this requires rice fields covering twice the surface area of the [Earth](#), oceans included. Another version of the story has the [inventor](#) losing his head.

It should be pointed out that as the emperor and the [inventor](#) went through the first half of the [chess](#) board, things were fairly uneventful. The [inventor](#) was given spoonfuls of rice, then bowls of rice, then barrels. By the end of the first half of the [chess](#) board, the [inventor](#) had accumulated one large field's worth (4 billion grains), and the emperor did start to take notice. It was as they [progressed](#) through the second half of the chessboard that the situation quickly deteriorated. Incidentally, with regard to the doublings of [computation](#), that's about where we stand now--there have been slightly more than 32 doublings of performance since the first [programmable computers](#) were invented during World War II.

This is the [nature](#) of [exponential growth](#). Although [technology](#) grows in the exponential [domain](#), we humans live in a [linear](#) world. So technological trends are not noticed as

small levels of technological power are doubled. Then seemingly out of nowhere, a [technology](#) explodes into view. For example, when the [Internet](#) went from 20,000 to 80,000 nodes over a two year period during the 1980s, this [progress](#) remained hidden from the general public. A decade later, when it went from 20 million to 80 million nodes in the same amount of [time](#), the impact was rather conspicuous.

As [exponential growth](#) continues to accelerate into the first half of the twenty-first century, it will appear to explode into [infinity](#), at least from the limited and [linear](#) perspective of contemporary humans. The [progress](#) will ultimately become so fast that it will rupture our ability to follow it. It will literally get out of our control. The illusion that we have our hand "on the plug," will be dispelled.

Can the pace of technological [progress](#) continue to speed up indefinitely? Is there not a point where humans are unable to think fast enough to keep up with it? With regard to unenhanced humans, clearly so. But what would a thousand scientists, each a thousand times more intelligent than [human](#) scientists today, and each operating a thousand times faster than contemporary humans (because the [information](#) processing in their primarily [nonbiological](#) brains is faster) accomplish? One year would be like a millennium. What would they come up with?

Well, for one thing, they would come up with [technology](#) to become even more intelligent (because their [intelligence](#) is no longer of fixed [capacity](#)). They would change their own [thought](#) processes to think even faster. When the scientists evolve to be a million times more intelligent and operate a million times faster, then an hour would result in a century of [progress](#) (in today's terms).

This, then, is the [Singularity](#). The [Singularity](#) is technological change so rapid and so profound that it represents a rupture in the fabric of [human history](#). Some would say that we cannot comprehend the [Singularity](#), at least with our current level of understanding, and that it is impossible, therefore, to look past its "[event horizon](#)" and make [sense](#) of what lies beyond.

My view is that despite our profound limitations of [thought](#), constrained as we are today to a mere hundred trillion interneuronal connections in our [biological](#) brains, we nonetheless have sufficient powers of [abstraction](#) to make meaningful statements about the [nature](#) of [life](#) after the [Singularity](#). Most [importantly](#), it is my view that the [intelligence](#) that will emerge will continue to represent the [human civilization](#), which is already a [human-machine civilization](#). This will be the next step in [evolution](#), the next high level [paradigm shift](#).

To put the [concept](#) of [Singularity](#) into perspective, let's explore the [history](#) of the word itself. [Singularity](#) is a familiar word meaning a unique [event](#) with profound implications. In [mathematics](#), the term implies [infinity](#), the explosion of value that occurs when dividing a constant by a [number](#) that gets closer and closer to zero. In [physics](#), similarly, a [singularity](#) denotes an [event](#) or location of infinite power. At the center of a [black hole](#), [matter](#) is so dense that its [gravity](#) is infinite. As nearby [matter](#) and [energy](#) are drawn into

the [black hole](#), an [event horizon](#) separates the region from the rest of the [Universe](#). It constitutes a rupture in the fabric of [space](#) and [time](#). The [Universe](#) itself is said to have begun with just such a [Singularity](#).

In the 1950s, John Von Neumann was quoted as saying that "the ever accelerating [progress](#) of [technology](#)...gives the appearance of approaching some essential [singularity](#) in the [history](#) of the race beyond which [human](#) affairs, as we know them, could not continue." In the 1960s, I. J. Good wrote of an "[intelligence](#) explosion," resulting from intelligent [machines](#) designing their next generation without [human](#) intervention. In 1986, [Vernor Vinge](#), a mathematician and [computer](#) scientist at San Diego State University, wrote about a rapidly approaching technological "[singularity](#)" in his [science fiction novel](#), *Marooned in Realtime*. Then in 1993, Vinge presented a paper to a [NASA](#)-organized symposium which described the [Singularity](#) as an impending [event](#) resulting primarily from the advent of "entities with greater than [human intelligence](#)," which Vinge saw as the harbinger of a run-away [phenomenon](#).

From my perspective, the [Singularity](#) has many faces. It represents the nearly vertical phase of [exponential growth](#) where the rate of [growth](#) is so extreme that [technology](#) appears to be growing at infinite speed. Of course, from a mathematical perspective, there is no discontinuity, no rupture, and the [growth](#) rates remain finite, albeit extraordinarily large. But from our *currently* limited perspective, this imminent [event](#) appears to be an acute and abrupt break in the continuity of [progress](#). However, I emphasize the word "currently," because one of the [salient](#) implications of the [Singularity](#) will be a change in the [nature](#) of our ability to understand. In other words, we will become vastly smarter as we [merge](#) with our [technology](#).

When I wrote my first book, *The [Age of Intelligent Machines](#)*, in the 1980s, I ended the book with the specter of the emergence of [machine intelligence](#) greater than [human intelligence](#), but found it difficult to look beyond this [event horizon](#). Now having [thought](#) about its implications for the past 20 years, I feel that we are indeed capable of understanding the many facets of this threshold, one that will transform all spheres of [human life](#).

Consider a few examples of the implications. The bulk of our [experiences](#) will shift from real [reality](#) to [virtual reality](#). Most of the [intelligence](#) of our [civilization](#) will ultimately be [nonbiological](#), which by the end of this century will be trillions of trillions of times more powerful than [human intelligence](#). However, to address often expressed concerns, this does not imply the end of [biological intelligence](#), even if thrown from its perch of [evolutionary](#) superiority. Moreover, it is [important](#) to note that the [nonbiological](#) forms will be derivative of [biological](#) design. In other words, our [civilization](#) will remain [human](#), indeed in many ways more exemplary of what we regard as [human](#) than it is today, although our understanding of the term will move beyond its strictly [biological](#) origins.

Many observers have nonetheless expressed alarm at the emergence of forms of [nonbiological intelligence](#) superior to [human intelligence](#). The potential to augment our

own [intelligence](#) through intimate connection with other [thinking](#) mediums does not necessarily alleviate the concern, as some people have expressed the wish to remain "unenhanced" while at the same [time](#) keeping their place at the top of the intellectual food chain. My view is that the likely outcome is that on the one hand, from the perspective of [biological](#) humanity, these superhuman [intelligences](#) will appear to be their transcendent servants, satisfying their needs and desires. On the other hand, fulfilling the wishes of a revered [biological](#) legacy will occupy only a trivial portion of the intellectual power that the [Singularity](#) will bring.

Needless to say, the [Singularity](#) will transform all aspects of our lives, social, sexual, and economic, which I explore herewith.

Wherefrom [Moore's Law](#)

Before considering further the implications of the [Singularity](#), let's examine the wide range of technologies that are subject to the [law of accelerating returns](#). The [exponential trend](#) that has gained the greatest public recognition has become known as "[Moore's Law](#)." [Gordon Moore](#), one of the [inventors](#) of [integrated circuits](#), and then Chairman of Intel, noted in the mid 1970s that we could squeeze twice as many [transistors](#) on an [integrated circuit](#) every 24 months. Given that the [electrons](#) have less distance to travel, the [circuits](#) also run twice as fast, providing an overall quadrupling of [computational](#) power.

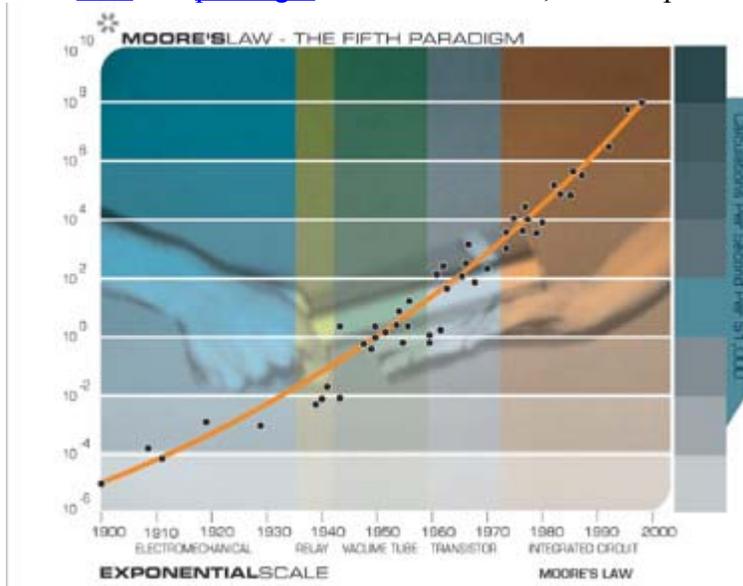
After sixty years of devoted service, [Moore's Law](#) will die a dignified [death](#) no later than the year 2019. By that [time](#), [transistor](#) features will be just a few atoms in width, and the strategy of ever finer photolithography will have run its course. So, will that be the end of the [exponential growth](#) of computing?

Don't bet on it.

If we plot the speed (in instructions per second) per \$1000 (in constant dollars) of 49 famous [calculator](#)s and [computer](#)s spanning the entire twentieth century, we note some interesting observations.

[Moore's Law](#) Was Not the First, but the Fifth [Paradigm](#) To Provide [Exponential Growth](#) of Computing

Each [time](#) one [paradigm](#) runs out of steam, another picks up the pace



It is [important](#) to note that [Moore's Law](#) of [Integrated Circuits](#) was not the first, but the fifth [paradigm](#) to provide accelerating [price-performance](#). Computing [devices](#) have been consistently multiplying in power (per unit of [time](#)) from the mechanical calculating [devices](#) used in the 1890 U.S. Census, to Turing's relay-based "[Robinson](#)" [machine](#) that cracked the Nazi [enigma code](#), to the CBS [vacuum tube computer](#) that predicted the election of Eisenhower, to the [transistor](#)-based [machines](#) used in the first [space](#) launches, to the integrated-[circuit](#)-based [personal computer](#) which I used to dictate (and automatically transcribe) this essay.

But I noticed something else surprising. When I plotted the 49 [machines](#) on an exponential graph (where a straight line means [exponential growth](#)), I didn't get a straight line. What I got was another exponential curve. In other words, there's [exponential growth](#) in the rate of [exponential growth](#). [Computer](#) speed (per unit cost) doubled every three years between 1910 and 1950, doubled every two years between 1950 and 1966, and is now doubling every year.

But where does [Moore's Law](#) come from? What is behind this remarkably predictable [phenomenon](#)? I have seen relatively little written about the ultimate source of this trend. Is it just "a [set](#) of industry expectations and goals," as Randy Isaac, head of [basic science](#) at [IBM](#) contends? Or is there something more profound going on?

In my view, it is one manifestation (among many) of the [exponential growth](#) of the [evolutionary](#) process that is [technology](#). The [exponential growth](#) of computing is a marvelous quantitative example of the exponentially growing returns from an [evolutionary](#) process. We can also express the [exponential growth](#) of computing in terms of an accelerating pace: it took ninety years to achieve the first [MIPS](#) (million

instructions per second) per thousand dollars, now we add one [MIPS](#) per thousand dollars every day.

[Moore's Law](#) narrowly refers to the [number](#) of [transistors](#) on an [integrated circuit](#) of fixed size, and sometimes has been expressed even more narrowly in terms of [transistor](#) feature size. But rather than feature size (which is only one contributing factor), or even [number](#) of [transistors](#), I think the most appropriate measure to track is [computational](#) speed per unit cost. This takes into account many levels of "cleverness" (i.e., innovation, which is to say, technological [evolution](#)). In addition to all of the innovation in [integrated circuits](#), there are multiple layers of innovation in [computer](#) design, e.g., pipelining, [parallel processing](#), instruction look-ahead, instruction and [memory](#) caching, and many others.

From the above chart, we see that the [exponential growth](#) of computing didn't start with [integrated circuits](#) (around 1958), or even [transistors](#) (around 1947), but goes back to the electromechanical [calculators](#) used in the 1890 and 1900 U.S. Census. This chart spans at least five distinct [paradigms](#) of computing, of which [Moore's Law](#) pertains to only the latest one.

It's obvious what the sixth [paradigm](#) will be after [Moore's Law](#) runs out of steam during the second decade of this century. Chips today are flat (although it does require up to 20 layers of material to produce one layer of [circuitry](#)). Our [brain](#), in contrast, is organized in three dimensions. We live in a three dimensional world, why not use the third dimension? The [human brain](#) actually uses a very inefficient electrochemical [digital](#) controlled [analog computational](#) process. The bulk of the calculations are done in the interneuronal connections at a speed of only about 200 calculations per second (in each connection), which is about ten million times slower than contemporary [electronic circuits](#). But the [brain](#) gains its prodigious powers from its extremely parallel organization *in three dimensions*. There are many technologies in the wings that build [circuitry](#) in three dimensions. [Nanotubes](#), for example, which are already working in laboratories, build [circuits](#) from pentagonal arrays of [carbon](#) atoms. One cubic inch of nanotube [circuitry](#) would be a million times more powerful than the [human brain](#). There are more than enough new computing technologies now being [researched](#), including three-dimensional [silicon](#) chips, optical computing, [crystalline computing](#), [DNA computing](#), and [quantum computing](#), to keep the [law of accelerating returns](#) as applied to [computation](#) going for a long [time](#).

Thus the (double) [exponential growth](#) of computing is broader than [Moore's Law](#), which refers to only one of its [paradigms](#). And this accelerating [growth](#) of computing is, in turn, part of the yet broader [phenomenon](#) of the accelerating pace of any [evolutionary](#) process. Observers are quick to criticize extrapolations of an [exponential trend](#) on the basis that the trend is bound to run out of "resources." The classical example is when a [species](#) happens upon a new habitat (e.g., rabbits in Australia), the [species' numbers](#) will grow exponentially for a [time](#), but then hit a limit when resources such as food and [space](#) run out.

But the resources underlying the [exponential growth](#) of an [evolutionary](#) process are relatively unbounded:

1. (i) The (ever growing) [order](#) of the [evolutionary](#) process itself. Each stage of [evolution](#) provides more powerful tools for the next. In [biological evolution](#), the advent of [DNA](#) allowed more powerful and faster [evolutionary "experiments."](#) Later, setting the "designs" of [animal](#) body plans during the [Cambrian](#) explosion allowed rapid [evolutionary](#) development of other body organs such as the [brain](#). Or to take a more recent example, the advent of [computer](#) assisted design tools allows rapid development of the next generation of [computers](#).
2. (ii) The "[chaos](#)" of the environment in which the [evolutionary](#) process takes place and which provides the options for further [diversity](#). In [biological evolution](#), [diversity](#) enters the process in the form of mutations and ever changing environmental conditions. In technological [evolution](#), [human](#) ingenuity combined with ever changing market conditions keep the process of innovation going.

The maximum potential of [matter](#) and [energy](#) to contain intelligent processes is a valid issue. But according to my models, we won't approach those limits during this century (but this will become an issue within a couple of centuries).

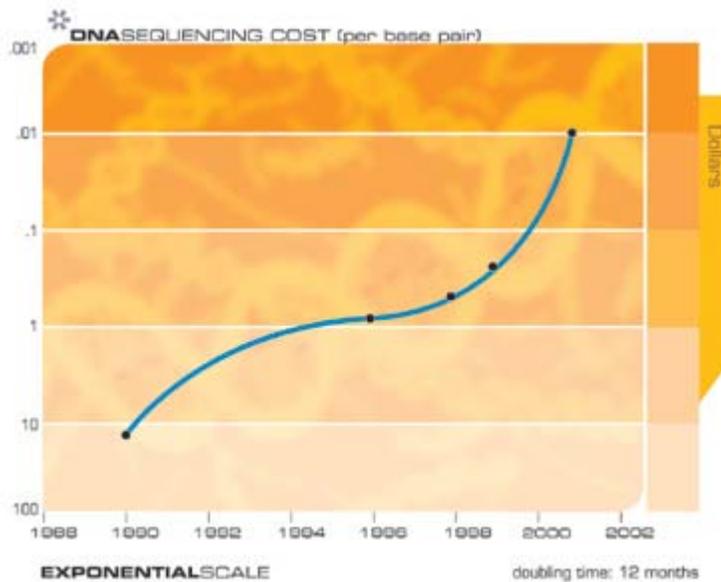
We also need to distinguish between the "S" curve (an "S" stretched to the right, comprising very slow, virtually unnoticeable [growth](#)--followed by very rapid [growth](#)--followed by a flattening out as the process approaches an asymptote) that is characteristic of any specific technological [paradigm](#) and the continuing [exponential growth](#) that is characteristic of the ongoing [evolutionary](#) process of [technology](#). Specific [paradigms](#), such as [Moore's Law](#), do ultimately reach levels at which [exponential growth](#) is no longer feasible. Thus [Moore's Law](#) is an S curve. But the [growth](#) of [computation](#) is an ongoing exponential (at least until we "saturate" the [Universe](#) with the [intelligence](#) of our [human-machine civilization](#), but that will not be a limit in this coming century). In accordance with the [law of accelerating returns](#), [paradigm shift](#), also called innovation, turns the S curve of any specific [paradigm](#) into a continuing exponential. A new [paradigm](#) (e.g., three-dimensional [circuits](#)) takes over when the old [paradigm](#) approaches its natural limit. This has already happened at least four times in the [history](#) of [computation](#). This difference also distinguishes the tool making of non-[human species](#), in which the mastery of a tool-making (or using) skill by each [animal](#) is characterized by an abruptly ending S shaped [learning](#) curve, versus [human-created technology](#), which has followed an exponential [pattern](#) of [growth](#) and acceleration since its inception.

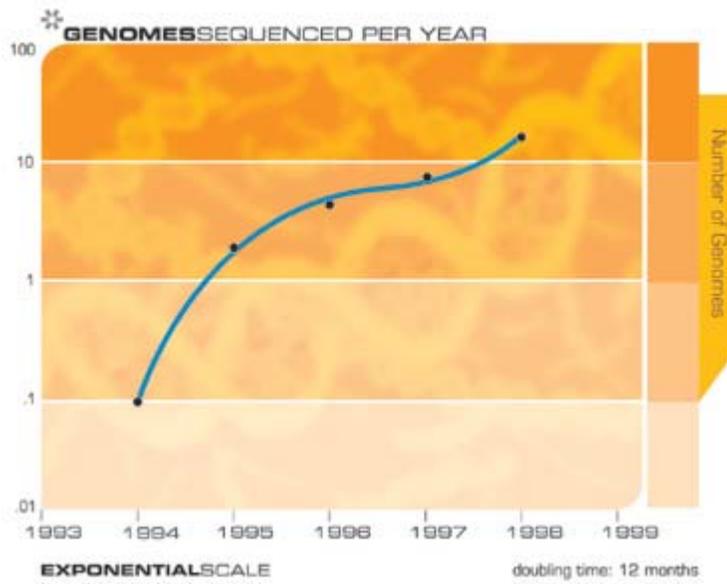
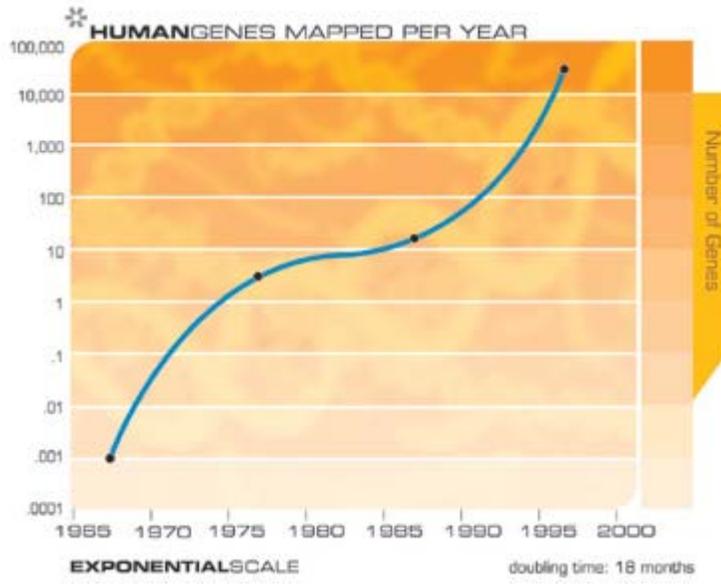
[DNA Sequencing](#), [Memory](#), [Communications](#), the [Internet](#), and [Miniaturization](#)

This "[law of accelerating returns](#)" applies to all of [technology](#), indeed to any true [evolutionary](#) process, and can be measured with remarkable precision in [information](#) based technologies. There are a great many examples of the [exponential growth](#) implied by the [law of accelerating returns](#) in technologies as varied as [DNA](#) sequencing,

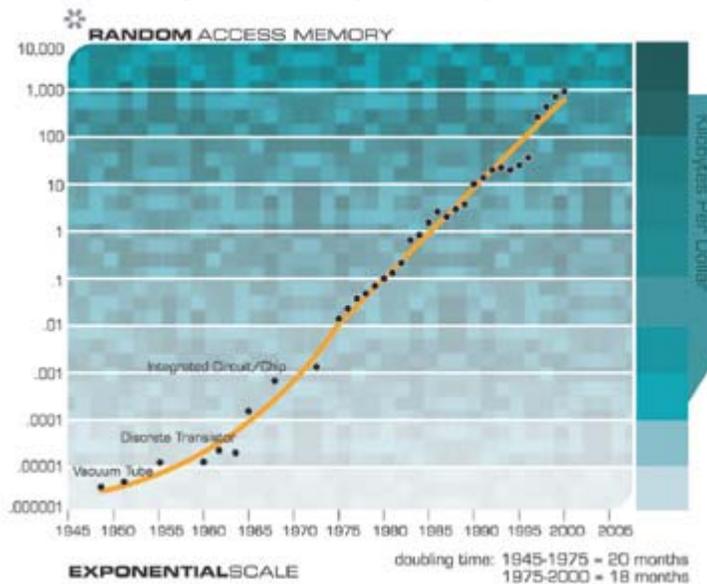
[communication](#) speeds, [electronics](#) of all kinds, and even in the rapidly shrinking size of [technology](#). The [Singularity](#) results not from the exponential explosion of [computation](#) alone, but rather from the interplay and myriad synergies that will result from manifold intertwined technological revolutions. Also, keep in [mind](#) that every point on the [exponential growth](#) curves underlying these panoply of technologies (see the graphs below) represents an intense [human](#) drama of innovation and competition. It is remarkable therefore that these chaotic processes result in such smooth and predictable [exponential trends](#).

For example, when the [human genome](#) scan started fourteen years ago, critics pointed out that given the speed with which the [genome](#) could then be scanned, it would take thousands of years to finish the project. Yet the fifteen year project was nonetheless completed slightly ahead of schedule.



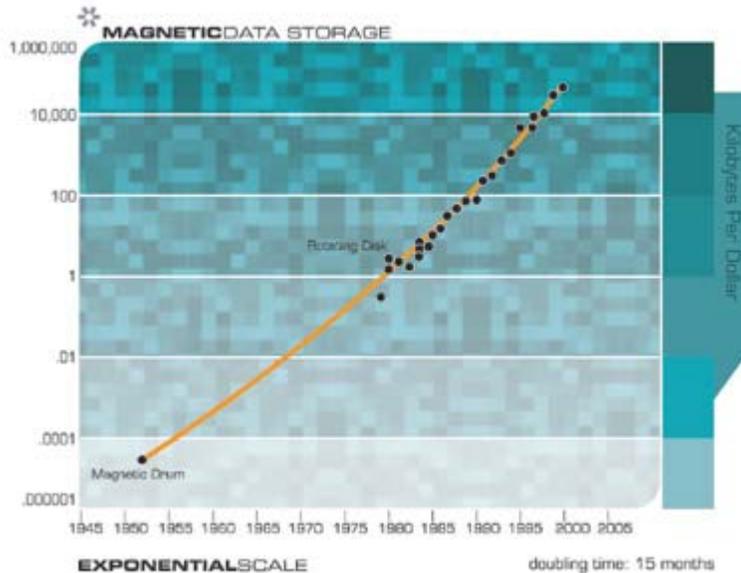


Of course, we expect to see [exponential growth](#) in [electronic](#) memories such as [RAM](#).



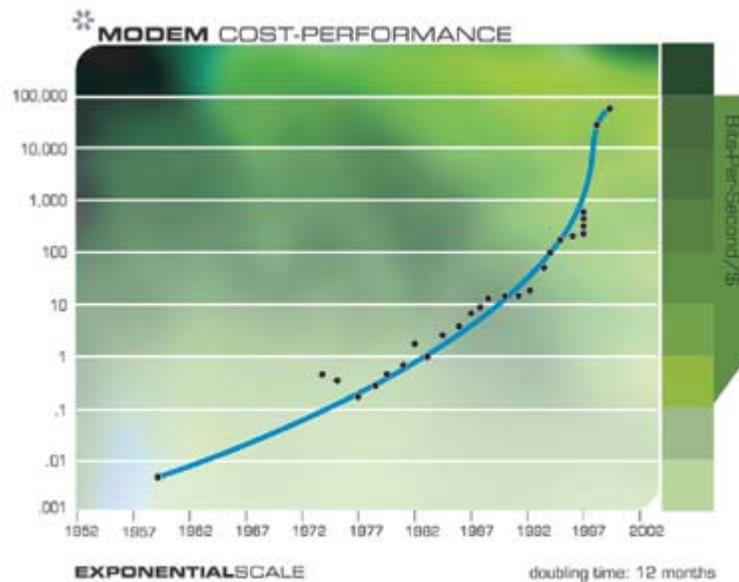
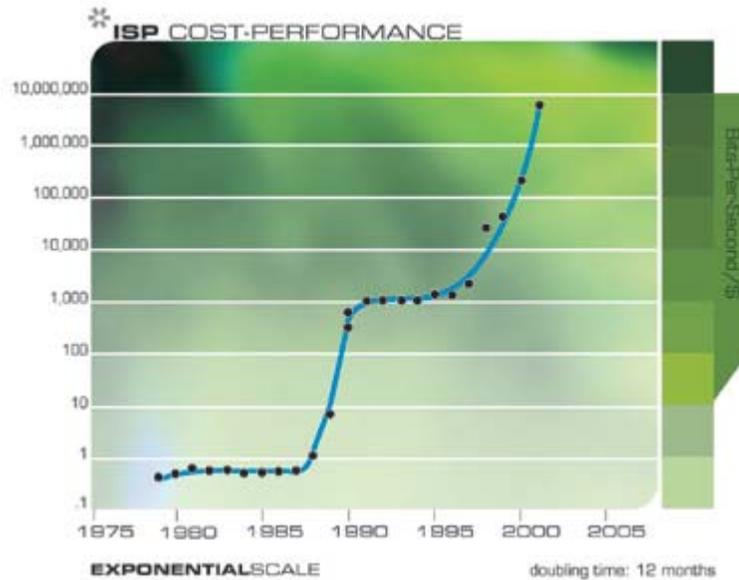
Notice How [Exponential Growth](#) Continued through [Paradigm Shifts](#) from [Vacuum Tubes](#) to [Discrete Transistors](#) to [Integrated Circuits](#)

However, [growth](#) in magnetic [memory](#) is not primarily a [matter](#) of [Moore's law](#), but includes advances in mechanical and [electromagnetic systems](#).



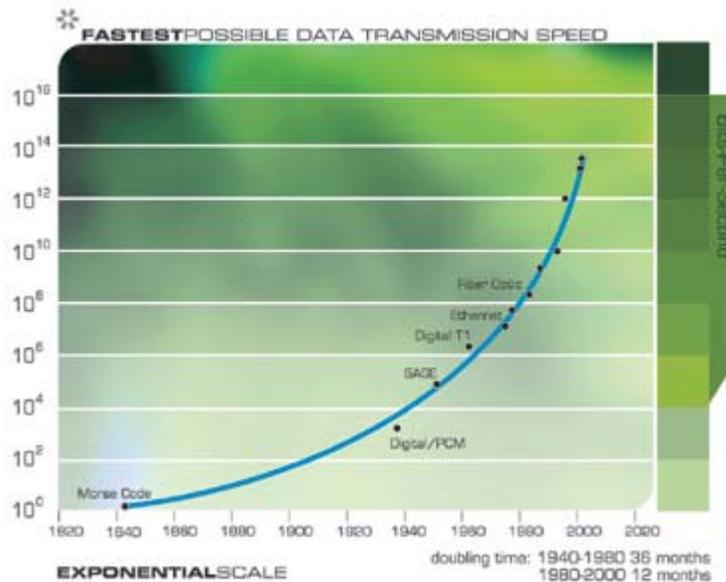
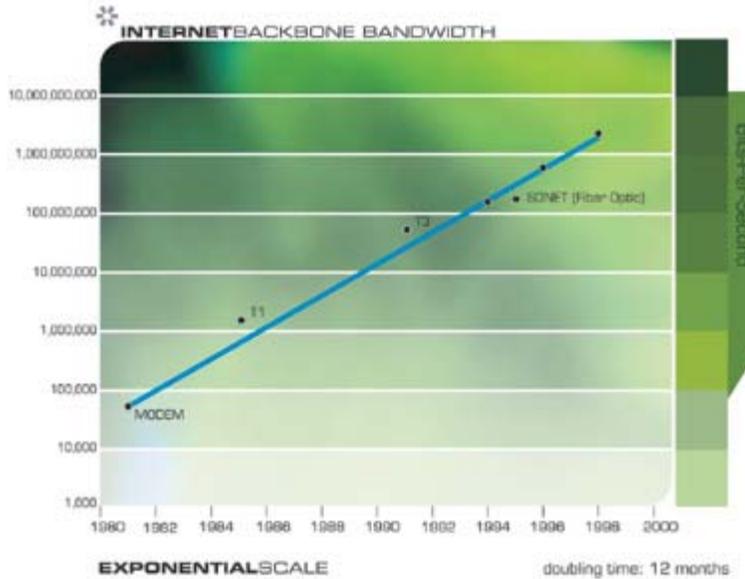
[Exponential growth](#) in [communication technology](#) has been even more explosive than in [computation](#) and is no less significant in its implications. Again, this [progression](#) involves

far more than just shrinking [transistors](#) on an [integrated circuit](#), but includes accelerating advances in [fiber optics](#), optical [switching](#), [electromagnetic](#) technologies, and others.

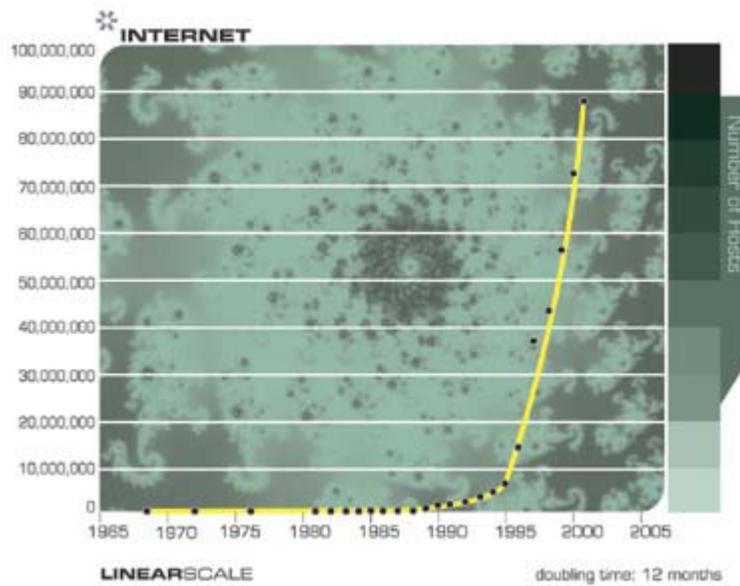
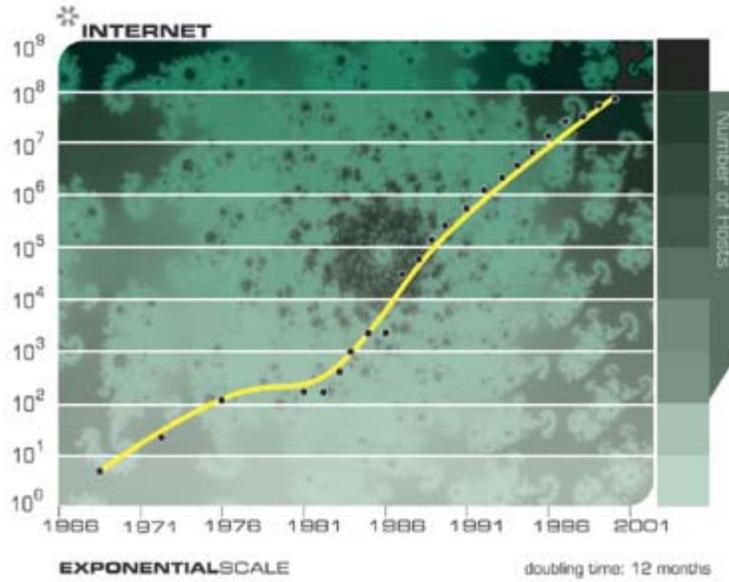


Notice Cascade of smaller "S" Curves

Note that in the above two charts we can actually see the [progression](#) of "S" curves: the acceleration fostered by a new [paradigm](#), followed by a leveling off as the [paradigm](#) runs out of steam, followed by renewed acceleration through [paradigm shift](#).

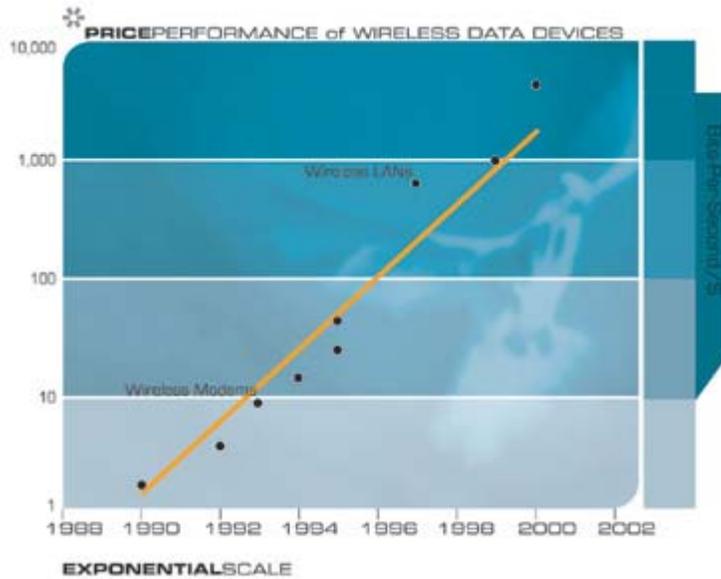


The following two charts show the overall [growth](#) of the [Internet](#) based on the [number](#) of hosts. These two charts plot the same [data](#), but one is on an exponential axis and the other is [linear](#). As I pointed out earlier, whereas [technology progresses](#) in the exponential [domain](#), we [experience](#) it in the [linear domain](#). So from the perspective of most observers, nothing was happening until the mid 1990s when seemingly out of nowhere, the [world wide web](#) and [email](#) exploded into view. But the emergence of the [Internet](#) into a worldwide [phenomenon](#) was readily predictable much earlier by examining the [exponential trend data](#).

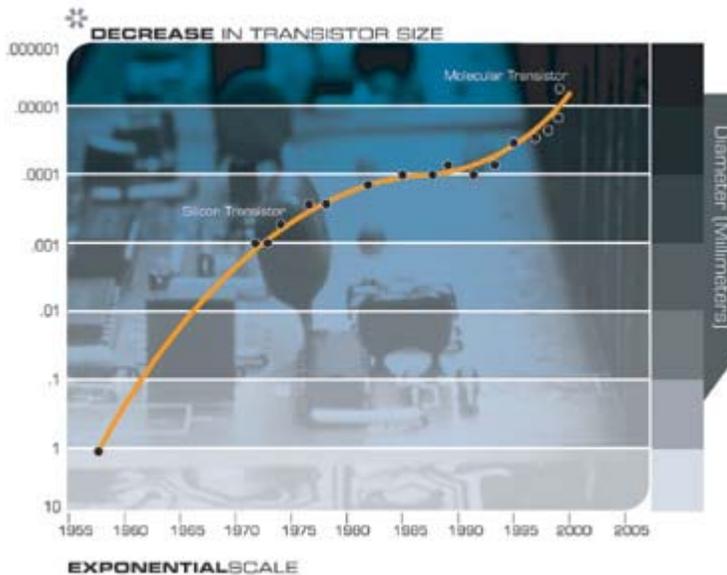


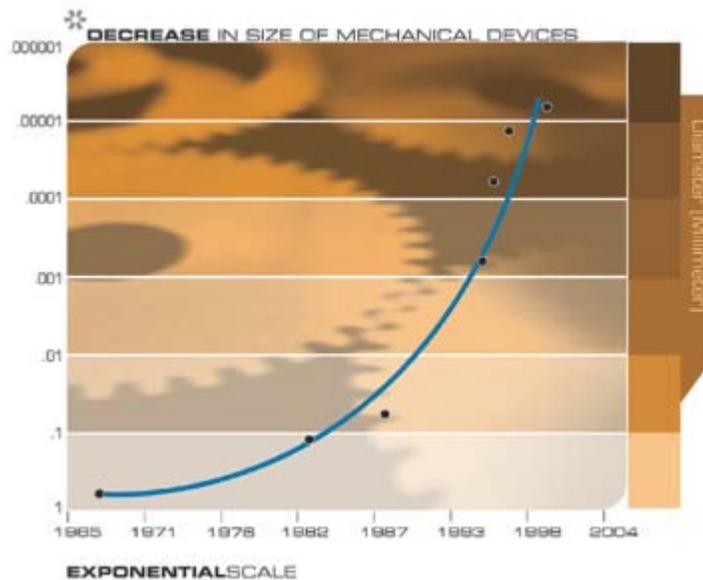
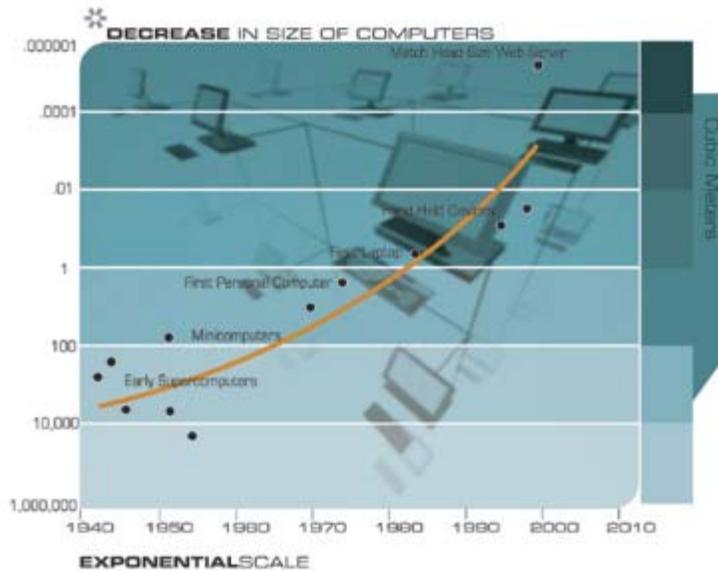
Notice how the explosion of the [Internet](#) appears to be a surprise from the [Linear](#) Chart, but was perfectly predictable from the Exponential Chart

Ultimately we will get away from the tangle of wires in our cities and in our lives through [wireless communication](#), the power of which is doubling every 10 to 11 months.



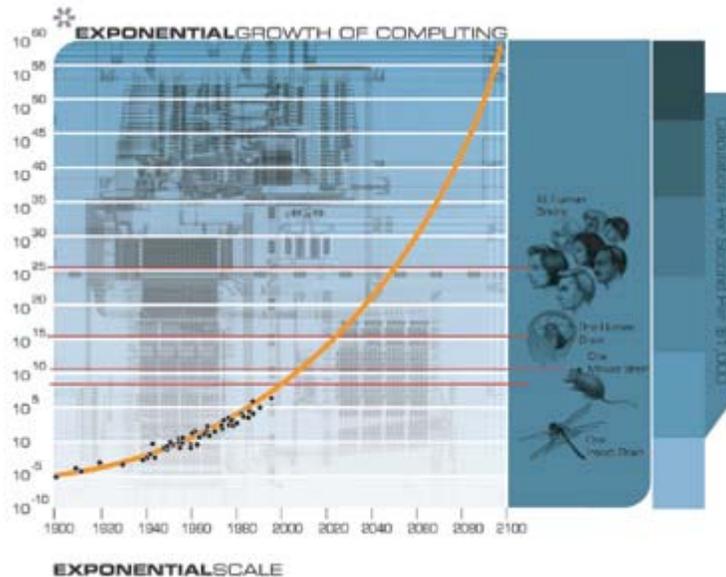
Another [technology](#) that will have profound implications for the twenty-first century is the pervasive trend toward making things smaller, i.e., [miniaturization](#). The [salient implementation](#) sizes of a broad range of technologies, both [electronic](#) and mechanical, are shrinking, also at a double exponential rate. At present, we are shrinking [technology](#) by a factor of approximately 5.6 per [linear](#) dimension per decade.





The Exponential Growth of Computation Revisited

If we view the exponential growth of computation in its proper perspective as one example of the pervasiveness of the exponential growth of information based technology, that is, as one example of many of the law of accelerating returns, then we can confidently predict its continuation.



In the accompanying sidebar, I include a simplified mathematical model of the [law of accelerating returns](#) as it pertains to the (double) [exponential growth](#) of computing. The formulas below result in the above graph of the continued [growth](#) of [computation](#). This graph matches the available [data](#) for the twentieth century through all five [paradigms](#) and provides projections for the twenty-first century. Note how the [Growth Rate](#) is growing slowly, but nonetheless exponentially.

The Law of Accelerating Returns Applied to the Growth of Computation

The following provides a brief overview of the [law of accelerating returns](#) as it applies to the double [exponential growth](#) of [computation](#). This model considers the impact of the growing power of the [technology](#) to foster its own next generation. For example, with more powerful [computers](#) and related [technology](#), we have the tools and the [knowledge](#) to design yet more powerful [computers](#), and to do so more quickly.

Note that the [data](#) for the year 2000 and beyond assume neural net connection calculations as it is expected that this type of calculation will ultimately dominate, particularly in emulating [human brain](#) functions. This type of calculation is less expensive than conventional (e.g., Pentium III / IV) calculations by a factor of at least 100 (particularly if [implemented](#) using [digital](#) controlled [analog electronics](#), which would correspond well to the [brain's](#) [digital](#) controlled [analog](#) electrochemical processes). A factor of 100 translates into approximately 6 years (today) and less than 6 years later in the twenty-first century.

My estimate of [brain capacity](#) is 100 billion [neurons](#) times an average 1,000 connections per [neuron](#) (with the calculations taking place primarily in the connections) times 200

calculations per second. Although these estimates are conservatively high, one can find higher and lower estimates. However, even much higher (or lower) estimates by orders of magnitude only shift the prediction by a relatively small [number](#) of years.

Some prominent dates from this analysis include the following:

- We achieve one [Human Brain](#) capability ($2 * 10^{16}$ cps) for \$1,000 around the year 2023.
- We achieve one [Human Brain](#) capability ($2 * 10^{16}$ cps) for one cent around the year 2037.
- We achieve one [Human](#) Race capability ($2 * 10^{26}$ cps) for \$1,000 around the year 2049.
- We achieve one [Human](#) Race capability ($2 * 10^{26}$ cps) for one cent around the year 2059.

The Model considers the following variables:

- V: [Velocity](#) (i.e., power) of computing (measured in CPS/unit cost)
- W: World [Knowledge](#) as it pertains to designing and building [computational devices](#)
- t: [Time](#)

The assumptions of the model are:

1. (1) $V = C1 * W$

In other words, [computer](#) power is a [linear](#) function of the [knowledge](#) of how to build [computers](#). This is actually a conservative assumption. In general, innovations improve V ([computer](#) power) by a multiple, not in an additive way. Independent innovations multiply each other's effect. For example, a [circuit](#) advance such as CMOS, a more efficient IC wiring [methodology](#), and a processor innovation such as pipelining all increase V by independent multiples.

• (2) $W = C2 * \text{Integral}(0 \text{ to } t) V$

In other words, W ([knowledge](#)) is cumulative, and the instantaneous increment to [knowledge](#) is proportional to V.

This gives us:

- $W = C1 * C2 * \text{Integral}(0 \text{ to } t) W$
- $W = C1 * C2 * C3^{(C4 * t)}$
- $V = C1^2 * C2 * C3^{(C4 * t)}$
- (Note on notation: a^b means a raised to the b power.)

Simplifying the constants, we get:

- $V = C_a * C_b ^{(C_c * t)}$

So this is a formula for "accelerating" (i.e., exponentially growing) returns, a "regular [Moore's Law](#)."

As I mentioned above, the [data](#) shows [exponential growth](#) in the rate of [exponential growth](#). (We doubled [computer](#) power every three years early in the twentieth century, every two years in the middle of the century, and close to every one year during the 1990s.)

Let's factor in another exponential [phenomenon](#), which is the growing resources for [computation](#). Not only is each (constant cost) [device](#) getting more powerful as a function of W, but the resources deployed for [computation](#) are also growing exponentially.

We now have:

- N: Expenditures for [computation](#)
- $V = C_1 * W$ (as before)
- $N = C_4 ^{(C_5 * t)}$ (Expenditure for [computation](#) is growing at its own exponential rate)
- $W = C_2 * \text{Integral}(0 \text{ to } t) (N * V)$

As before, world [knowledge](#) is accumulating, and the instantaneous increment is proportional to the amount of [computation](#), which equals the resources deployed for [computation](#) (N) * the power of each (constant cost) [device](#).

This gives us:

- $W = C_1 * C_2 * \text{Integral}(0 \text{ to } t) (C_4 ^{(C_5 * t)} * W)$
- $W = C_1 * C_2 * (C_3 ^{(C_6 * t)}) ^{(C_7 * t)}$
- $V = C_1 ^2 * C_2 * (C_3 ^{(C_6 * t)}) ^{(C_7 * t)}$

Simplifying the constants, we get:

- $V = C_a * (C_b ^{(C_c * t)}) ^{(C_d * t)}$

This is a double exponential--an exponential curve in which the rate of [exponential growth](#) is growing at a different exponential rate.

Now let's consider real-world [data](#). Considering the [data](#) for actual calculating [devices](#) and [computers](#) during the twentieth century:

- CPS/\$1K: Calculations Per Second for \$1,000

Twentieth century computing [data](#) matches:

- $\text{CPS}/\$1\text{K} = 10^{(6.00 * ((20.40/6.00)^{(A13-1900)/100)) - 11.00)}$

We can determine the [growth](#) rate over a period of time:

- [Growth](#) Rate = $10^{((\text{LOG}(\text{CPS}/\$1\text{K for Current Year}) - \text{LOG}(\text{CPS}/\$1\text{K for Previous Year})) / (\text{Current Year} - \text{Previous Year}))}$
- [Human Brain](#) = 100 Billion (10^{11}) [neurons](#) * 1000 (10^3) Connections/[Neuron](#) * 200 ($2 * 10^2$) Calculations Per Second Per Connection = $2 * 10^{16}$ Calculations Per Second
- [Human](#) Race = 10 Billion (10^{10}) [Human](#) Brains = $2 * 10^{26}$ Calculations Per Second

These formulas produce the graph above.

Already, [IBM's "Blue Gene" supercomputer](#), now being built and scheduled to be completed by 2005, is projected to provide 1 million billion calculations per second (i.e., one billion megaflops). This is already one twentieth of the [capacity](#) of the [human brain](#), which I estimate at a conservatively high 20 million billion calculations per second (100 billion [neurons](#) times 1,000 connections per [neuron](#) times 200 calculations per second per connection). In line with my earlier predictions, [supercomputers](#) will achieve one [human brain capacity](#) by 2010, and [personal computers](#) will do so by around 2020. By 2030, it will take a village of [human](#) brains (around a thousand) to match \$1000 of computing. By 2050, \$1000 of computing will equal the processing power of all [human](#) brains on [Earth](#). Of course, this only includes those brains still using [carbon](#)-based [neurons](#). While [human neurons](#) are wondrous creations in a way, we wouldn't (and don't) design computing [circuits](#) the same way. Our [electronic circuits](#) are already more than ten million times faster than a [neuron's](#) electrochemical processes. Most of the [complexity](#) of a [human neuron](#) is devoted to maintaining its [life](#) support functions, not its [information](#) processing capabilities. Ultimately, we will need to [port](#) our mental processes to a more suitable [computational substrate](#). Then our minds won't have to stay so small, being constrained as they are today to a mere hundred trillion neural connections each operating at a ponderous 200 [digital](#)ly controlled [analog](#) calculations per second.

The Software of Intelligence

So far, I've been talking about the [hardware](#) of computing. The [software](#) is even more [salient](#). One of the principal assumptions underlying the expectation of the [Singularity](#) is the ability of [nonbiological](#) mediums to emulate the richness, subtlety, and depth of [human thinking](#). Achieving the [computational capacity](#) of the [human brain](#), or even villages and nations of [human](#) brains will not automatically produce [human](#) levels of capability. By [human](#) levels I include all the diverse and subtle ways in which humans are intelligent, including musical and artistic aptitude, [creativity](#), physically moving through the world, and understanding and responding appropriately to [emotion](#). The requisite [hardware capacity](#) is a necessary but not sufficient condition. The organization and [content](#) of these resources--the [software](#) of [intelligence](#)--is also critical.

Before addressing this issue, it is [important](#) to note that once a [computer](#) achieves a [human](#) level of [intelligence](#), it will necessarily soar past it. A key advantage of [nonbiological intelligence](#) is that [machines](#) can easily share their [knowledge](#). If I learn French, or read War and Peace, I can't readily [download](#) that [learning](#) to you. You have to acquire that scholarship the same painstaking way that I did. My [knowledge](#), embedded in a vast [pattern](#) of [neurotransmitter](#) concentrations and interneuronal connections, cannot be quickly [accessed](#) or transmitted. But we won't leave out quick [download](#)ing ports in our [nonbiological](#) equivalents of [human neuron](#) clusters. When one [computer](#) learns a skill or gains an insight, it can immediately share that [wisdom](#) with billions of other [machines](#).

As a contemporary example, we spent years teaching one [research computer](#) how to recognize continuous [human](#) speech. We exposed it to thousands of hours of recorded speech, corrected its errors, and patiently improved its performance. Finally, it became quite adept at recognizing speech (I dictated most of my recent book to it). Now if you want your own [personal computer](#) to recognize speech, it doesn't have to go through the same process; you can just [download](#) the fully trained [patterns](#) in seconds. Ultimately, billions of [nonbiological](#) entities can be the master of all [human](#) and [machine](#) acquired [knowledge](#).

In addition, [computers](#) are potentially millions of times faster than [human](#) neural [circuits](#). A [computer](#) can also remember billions or even trillions of facts perfectly, while we are hard pressed to remember a handful of phone [numbers](#). The combination of [human](#) level [intelligence](#) in a [machine](#) with a [computer's](#) inherent superiority in the speed, accuracy, and sharing ability of its [memory](#) will be formidable.

There are a [number](#) of compelling scenarios to achieve higher levels of [intelligence](#) in our [computers](#), and ultimately [human](#) levels and beyond. We will be able to evolve and train a [system](#) combining massively parallel neural nets with other [paradigms](#) to understand [language](#) and model [knowledge](#), including the ability to read and model the [knowledge](#) contained in written documents. Unlike many contemporary "neural net" [machines](#), which use mathematically simplified models of [human neurons](#), some contemporary neural nets are already using highly detailed models of [human neurons](#), including detailed nonlinear [analog](#) activation functions and other relevant details. Although the ability of today's [computers](#) to extract and learn [knowledge](#) from [natural language](#) documents is limited, their capabilities in this [domain](#) are improving rapidly. [Computers](#) will be able to read on their own, understanding and modeling what they have read, by the second decade of the twenty-first century. We can then have our [computers](#) read all of the world's literature--books, magazines, scientific journals, and other available material. Ultimately, the [machines](#) will gather [knowledge](#) on their own by venturing out on the web, or even into the physical world, drawing from the full spectrum of [media](#) and [information](#) services, and sharing [knowledge](#) with each other (which [machines](#) can do far more easily than their [human](#) creators).

[Reverse Engineering](#) the [Human Brain](#)

The most compelling scenario for mastering the [software](#) of [intelligence](#) is to tap into the blueprint of the best example we can get our hands on of an intelligent process. There is no [reason](#) why we cannot reverse [engineer](#) the [human brain](#), and essentially copy its design. Although it took its original designer several billion years to develop, it's readily available to us, and not (yet) [copyrighted](#). Although there's a skull around the [brain](#), it is not hidden from our view.

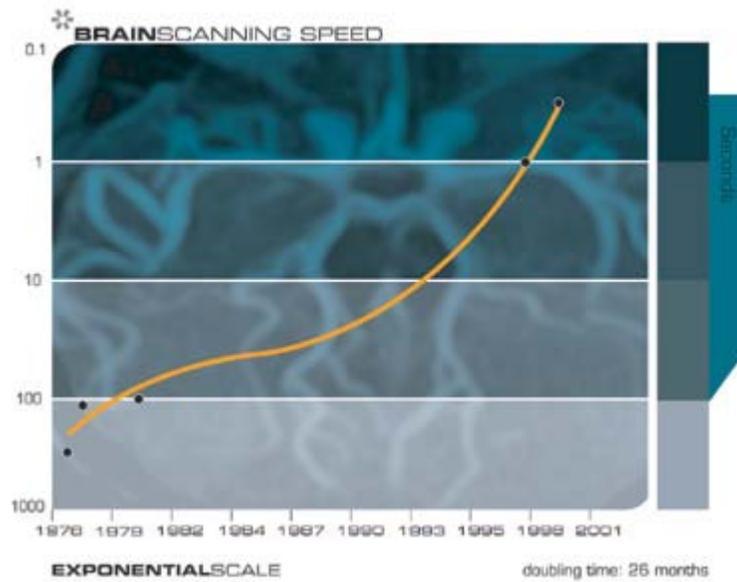
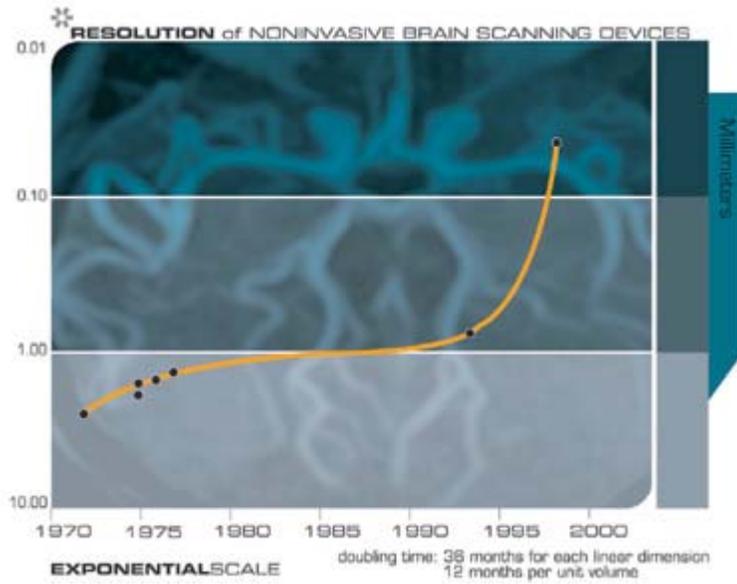
The most immediately [accessible](#) way to accomplish this is through destructive scanning: we take a frozen [brain](#), preferably one frozen just slightly before rather than slightly after it was going to die anyway, and examine one [brain](#) layer--one very thin slice--at a [time](#). We can readily see every [neuron](#) and every connection and every [neurotransmitter](#) concentration represented in each [synapse](#)-thin layer.

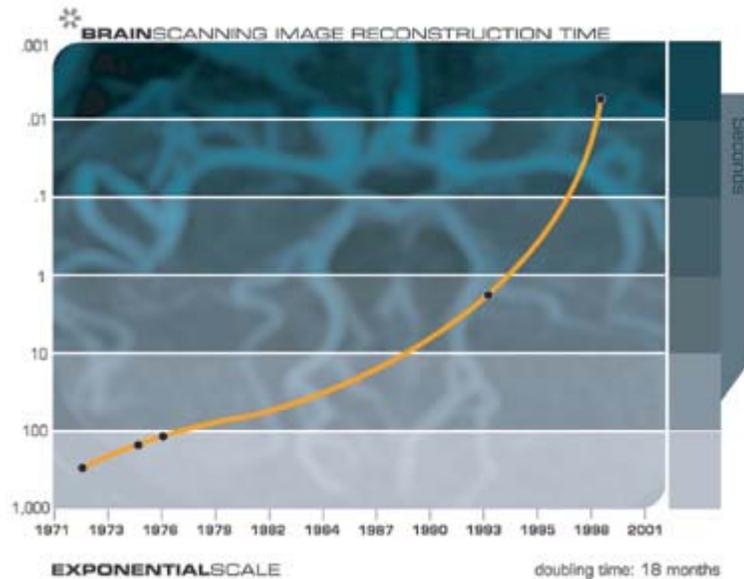
[Human brain scanning](#) has already started. A condemned killer allowed his [brain](#) and body to be scanned and you can [access](#) all 10 billion bytes of him on the [Internet](#) http://www.nlm.nih.gov/research/visible/visible_human.html.

He has a 25 billion [byte female](#) companion on the site as well in case he gets lonely. This scan is not high enough in resolution for our purposes, but then, we probably don't want to base our templates of [machine intelligence](#) on the [brain](#) of a convicted killer, anyway.

But scanning a frozen [brain](#) is feasible today, albeit not yet at a sufficient speed or [bandwidth](#), but again, the [law of accelerating returns](#) will provide the requisite speed of scanning, just as it did for the [human genome](#) scan. Carnegie Mellon University's Andreas Nowatzyk plans to scan the nervous [system](#) of the [brain](#) and body of a [mouse](#) with a resolution of less than 200 nanometers, which is getting very close to the resolution needed for [reverse engineering](#).

We also have noninvasive scanning techniques today, including high-resolution magnetic resonance imaging ([MRI](#)) scans, [optical imaging](#), near-infrared scanning, and other technologies which are capable in certain [instances](#) of resolving [individual](#) somas, or [neuron cell](#) bodies. [Brain scanning](#) technologies are also increasing their resolution with each new generation, just what we would expect from the [law of accelerating returns](#). [Future](#) generations will enable us to resolve the connections between [neurons](#) and to peer inside the [synapses](#) and record the [neurotransmitter](#) concentrations.





We can peer inside someone's [brain](#) today with noninvasive scanners, which are increasing their resolution with each new generation of this [technology](#). There are a [number](#) of technical challenges in accomplishing this, including achieving suitable resolution, [bandwidth](#), lack of vibration, and safety. For a variety of [reasons](#) it is easier to scan the [brain](#) of someone recently deceased than of someone still living. It is easier to get someone deceased to sit still, for one thing. But noninvasively scanning a living [brain](#) will ultimately become feasible as [MRI](#), optical, and other scanning technologies continue to improve in resolution and speed.

Scanning from Inside

Although noninvasive means of scanning the [brain](#) from outside the skull are rapidly improving, the most practical approach to capturing every [salient](#) neural detail will be to scan it from inside. By 2030, "[nanobot](#)" (i.e., nano [robot](#)) [technology](#) will be viable, and [brain scanning](#) will be a prominent application. [Nanobots](#) are robots that are the size of [human](#) blood cells, or even smaller. Billions of them could travel through every [brain](#) capillary and scan every relevant feature from up close. Using high speed [wireless communication](#), the [nanobots](#) would communicate with each other, and with other [computers](#) that are compiling the [brain scan data](#) base (in other words, the [nanobots](#) will all be on a [wireless local area network](#)).

This scenario involves only capabilities that we can touch and feel today. We already have [technology](#) capable of producing very high resolution scans, provided that the scanner is physically proximate to the neural features. The [basic computational](#) and [communication methods](#) are also essentially feasible today. The primary features that are not yet practical are [nanobot](#) size and cost. As I discussed above, we can project the exponentially declining cost of [computation](#), and the rapidly declining size of both [electronic](#) and mechanical technologies. We can conservatively expect, therefore, the

requisite [nanobot technology](#) by around 2030. Because of its ability to place each scanner in very close physical proximity to every neural feature, [nanobot](#)-based scanning will be more practical than scanning the [brain](#) from outside.

How to Use Your [Brain Scan](#)

How will we apply the thousands of trillions of bytes of [information](#) derived from each [brain scan](#)? One approach is to use the results to design more intelligent parallel [algorithms](#) for our [machines](#), particularly those based on one of the neural net [paradigms](#). With this approach, we don't have to copy every single connection. There is a great deal of repetition and redundancy within any particular [brain](#) region. Although the [information](#) contained in a [human brain](#) would require thousands of trillions of bytes of [information](#) (on the [order](#) of 100 billion [neurons](#) times an average of 1,000 connections per [neuron](#), each with multiple [neurotransmitter](#) concentrations and connection [data](#)), the design of the [brain](#) is characterized by a [human genome](#) of only about a billion bytes.

Furthermore, most of the [genome](#) is redundant, so the initial design of the [brain](#) is characterized by approximately one hundred million bytes, about the size of [Microsoft Word](#). Of course, the [complexity](#) of our brains greatly increases as we interact with the world (by a factor of more than ten million). Because of the highly repetitive [patterns](#) found in each specific [brain](#) region, it is not necessary to capture each detail in [order](#) to reverse [engineer](#) the significant [digital-analog algorithms](#). With this [information](#), we can design simulated nets that operate similarly. There are already multiple efforts under way to scan the [human brain](#) and apply the insights derived to the design of intelligent [machines](#).

The pace of [brain reverse engineering](#) is only slightly behind the availability of the [brain scanning](#) and [neuron structure information](#). A contemporary example is a comprehensive model of a significant portion of the [human](#) auditory processing [system](#) that [Lloyd Watts](#) (www.lloydwatts.com) has developed from both [neurobiology](#) studies of specific [neuron](#) types and [brain](#) interneuronal connection [information](#). Watts' model includes five parallel paths and includes the actual intermediate representations of auditory [information](#) at each stage of neural processing. Watts has [implemented](#) his model as real-time [software](#) which can locate and identify sounds with many of the same properties as [human](#) hearing. Although a work in [progress](#), the model illustrates the feasibility of converting neurobiological models and [brain](#) connection [data](#) into working simulations. Also, as [Hans Moravec](#) and others have speculated, these efficient simulations require about 1,000 times less [computation](#) than the theoretical potential of the [biological neurons](#) being simulated.

[Reverse Engineering](#) the [Human Brain](#): Five Parallel Auditory Pathways

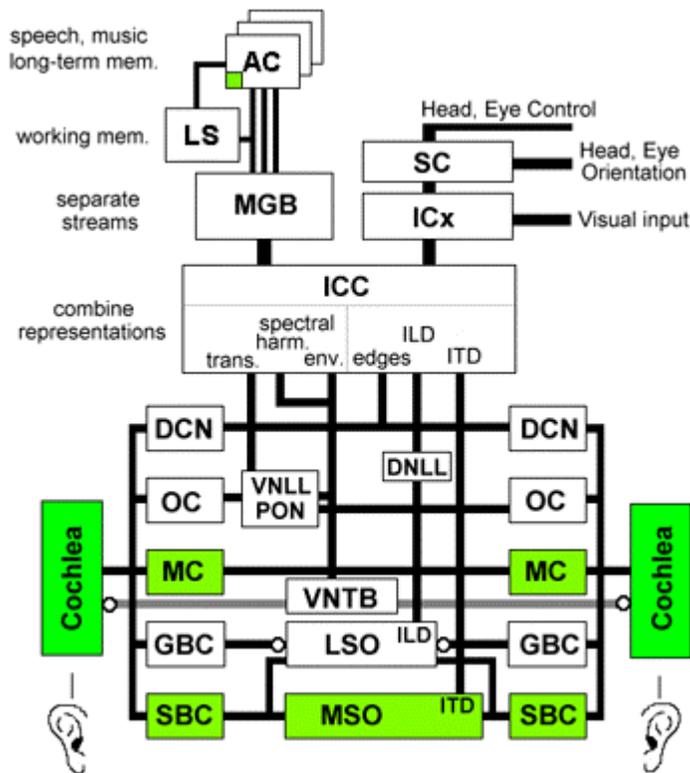


Chart by [Lloyd Watts](#)

Cochlea: [Sense](#) organ of hearing. 30,000 fibers converts [motion](#) of the stapes into spectro-temporal representation of sound.

MC: Multipolar Cells. Measure spectral [energy](#).

GBC: Globular Bushy Cells. Relays spikes from the auditory [nerve](#) to the Lateral Superior.

Olivary Complex (includes **LSO** and **MSO**). Encoding of timing and amplitude of signals for binaural comparison of level.

SBC: Spherical Bushy Cells. Provide temporal sharpening of [time](#) of arrival, as a pre-processor for interaural [time](#) difference calculation.

OC: Octopus Cells. Detection of [transients](#).

DCN: Dorsal Cochlear [Nucleus](#). Detection of spectral edges and calibrating for [noise](#) levels.

VNTB: Ventral [Nucleus](#) of the Trapezoid Body. Feedback signals to modulate outer hair [cell](#) function in the cochlea.

VNLL, PON: Ventral [Nucleus](#) of the Lateral Lemniscus, Peri-Olivary Nuclei. Processing [transients](#) from the Octopus Cells.

MSO: Medial Superior Olive. Computing inter-aural [time](#) difference (difference in [time](#) of arrival between the two ears, used to tell where a sound is coming from).

LSO: Lateral Superior Olive. Also involved in computing inter-aural level difference.

ICC: Central [Nucleus](#) of the Inferior Colliculus. The site of major integration of multiple representations of sound.

ICx: Exterior [Nucleus](#) of the Inferior Colliculus. Further refinement of sound localization.

SC: Superior Colliculus. Location of auditory/visual merging.

MGB: Medial Geniculate Body. The auditory portion of the thalamus.

LS: Limbic [System](#). Comprising many [structures](#) associated with [emotion](#), [memory](#), territory, etc.

AC: Auditory Cortex.

The [brain](#) is not one huge "[tabula rasa](#)" (i.e., undifferentiated blank slate), but rather an intricate and intertwined collection of hundreds of specialized regions. The process of "peeling the onion" to understand these interleaved regions is well underway. As the requisite [neuron](#) models and [brain](#) interconnection [data](#) becomes available, detailed and [implementable](#) models such as the auditory example above will be developed for all [brain](#) regions.

After the [algorithms](#) of a region are understood, they can be refined and extended before being [implemented](#) in synthetic neural equivalents. For one thing, they can be run on a [computational substrate](#) that is already more than ten million times faster than neural [circuitry](#). And we can also throw in the [methods](#) for building intelligent [machines](#) that we already understand.

[Downloading the Human Brain](#)

A more controversial application than this scanning-the-[brain](#)-to-understand-it scenario is *scanning-the-[brain](#)-to-download-it*. Here we scan someone's [brain](#) to map the locations, interconnections, and [contents](#) of all the somas, axons, dendrites, presynaptic vesicles, [neurotransmitter](#) concentrations, and other neural [components](#) and levels. Its entire organization can then be re-created on a [neural computer](#) of sufficient [capacity](#), including the [contents](#) of its [memory](#).

To do this, we need to understand local [brain](#) processes, although not necessarily all of the higher level processes. Scanning a [brain](#) with sufficient detail to [download](#) it may sound daunting, but so did the [human genome](#) scan. All of the [basic](#) technologies exist today, just not with the requisite speed, cost, and size, but these are the [attributes](#) that are improving at a double exponential pace.

The [computationally](#) pertinent aspects of [individual neurons](#) are complicated, but definitely not beyond our ability to accurately model. For example, Ted Berger and his colleagues at Hedco [Neurosciences](#) have built [integrated circuits](#) that precisely match the [digital](#) and [analog information](#) processing characteristics of [neurons](#), including clusters with hundreds of [neurons](#). [Carver Mead](#) and his colleagues at CalTech have built a variety of [integrated circuits](#) that emulate the [digital-analog](#) characteristics of [mammalian](#) neural [circuits](#).

A recent [experiment](#) at San Diego's Institute for Nonlinear [Science](#) demonstrates the potential for [electronic neurons](#) to precisely emulate [biological](#) ones. [Neurons](#) ([biological](#) or otherwise) are a prime example of what is often called "chaotic computing." Each [neuron](#) acts in an essentially unpredictable fashion. When an entire [network](#) of [neurons](#) receives input (from the outside world or from other [networks](#) of [neurons](#)), the signaling amongst them appears at first to be frenzied and random. Over [time](#), typically a fraction of a second or so, the chaotic interplay of the [neurons](#) dies down, and a stable [pattern](#) emerges. This [pattern](#) represents the "decision" of the [neural network](#). If the [neural network](#) is performing a [pattern recognition](#) task (which, incidentally, comprises the bulk of the activity in the [human brain](#)), then the emergent [pattern](#) represents the appropriate recognition.

So the question addressed by the San Diego [researchers](#) was whether [electronic neurons](#) could engage in this chaotic dance alongside [biological](#) ones. They hooked up their artificial [neurons](#) with those from spiny lobsters in a single [network](#), and their hybrid [biological-nonbiological network](#) performed in the same way (i.e., chaotic interplay followed by a stable emergent [pattern](#)) and with the same type of results as an all [biological](#) net of [neurons](#). Essentially, the [biological neurons](#) accepted their [electronic](#) peers. It indicates that their mathematical model of these [neurons](#) was [reasonably](#) accurate.

There are many projects around the world which are creating [nonbiological devices](#) to recreate in great detail the functionality of [human neuron](#) clusters. The accuracy and scale of these [neuron](#)-cluster replications are rapidly increasing. We started with functionally equivalent recreations of single [neurons](#), then clusters of tens, then hundreds, and now thousands. Scaling up technical processes at an exponential pace is what [technology](#) is good at.

As the [computational](#) power to emulate the [human brain](#) becomes available--we're not there yet, but we will be there within a couple of decades--projects already under way to scan the [human brain](#) will be accelerated, with a view both to understand the [human brain](#) in general, as well as providing a detailed description of the [contents](#) and design of

specific brains. By the third decade of the twenty-first century, we will be in a position to create highly detailed and complete maps of all relevant features of all [neurons](#), neural connections and [synapses](#) in the [human brain](#), all of the neural details that play a role in the behavior and functionality of the [brain](#), and to recreate these designs in suitably advanced [neural computers](#).

Is the [Human Brain](#) Different from a [Computer](#)?

Is the [human brain](#) different from a [computer](#)?

The answer depends on what we mean by the word "[computer](#)." Certainly the [brain](#) uses very different [methods](#) from conventional contemporary [computers](#). Most [computers](#) today are all [digital](#) and perform one (or perhaps a few) [computations](#) at a [time](#) at extremely high speed. In contrast, the [human brain](#) combines [digital](#) and [analog methods](#) with most [computations](#) performed in the [analog domain](#). The [brain](#) is massively parallel, performing on the [order](#) of a hundred trillion [computations](#) at the same [time](#), but at extremely slow speeds.

With regard to [digital](#) versus [analog](#) computing, we know that [digital](#) computing can be functionally equivalent to [analog](#) computing (although the reverse is not true), so we can perform all of the capabilities of a hybrid [digital--analog network](#) with an all [digital computer](#). On the other hand, there is an [engineering](#) advantage to [analog circuits](#) in that [analog](#) computing is potentially thousands of times more efficient. An [analog computation](#) can be performed by a few [transistors](#), or, in the case of [mammalian neurons](#), specific electrochemical processes. A [digital computation](#), in contrast, requires thousands or tens of thousands of [transistor](#)s. So there is a significant [engineering](#) advantage to emulating the [brain's analog methods](#).

The massive parallelism of the [human brain](#) is the key to its [pattern recognition](#) abilities, which reflects the strength of [human thinking](#). As I discussed above, [mammalian neurons](#) engage in a chaotic dance, and if the [neural network](#) has learned its lessons well, then a stable [pattern](#) will emerge reflecting the [network's](#) decision. There is no [reason](#) why our [nonbiological](#) functionally equivalent recreations of [biological neural networks](#) cannot be built using these same principles, and indeed there are dozens of projects around the world that have succeeded in doing this. My own technical field is [pattern recognition](#), and the projects that I have been involved in for over thirty years use this form of chaotic computing. Particularly successful examples are [Carver Mead's](#) neural chips, which are highly parallel, use [digital](#) controlled [analog](#) computing, and are intended as functionally similar recreations of [biological networks](#).

[Objective](#) and Subjective

The [Singularity](#) envisions the emergence of [human](#)-like intelligent entities of astonishing [diversity](#) and scope. Although these entities will be capable of passing the "[Turing test](#)" (i.e., able to fool humans that they are [human](#)), the question arises as to whether these

"people" are conscious, or just appear that way. To gain some insight as to why this is an extremely subtle question (albeit an ultimately [important](#) one) it is useful to consider some of the [paradoxes](#) that emerge from the [concept](#) of [download](#)ing specific [human](#) brains.

Although I anticipate that the most common application of the [knowledge](#) gained from [reverse engineering](#) the [human brain](#) will be creating more intelligent [machines](#) that are not necessarily modeled on specific [biological human individuals](#), the scenario of scanning and reinstantiating all of the neural details of a *specific* person raises the most immediate questions of [identity](#). Let's consider the question of what we will find when we do this.

We have to consider this question on both the [objective](#) and subjective levels. "[Objective](#)" means everyone except me, so let's start with that. [Objectively](#), when we scan someone's [brain](#) and restantiate their personal [mind file](#) into a suitable [computing medium](#), the newly emergent "person" will appear to other observers to have very much the same personality, [history](#), and [memory](#) as the person originally scanned. That is, once the [technology](#) has been refined and perfected. Like any new [technology](#), it won't be perfect at first. But ultimately, the scans and recreations will be very accurate and realistic.

Interacting with the newly instantiated person will feel like interacting with the original person. The new person will claim to be that same old person and will have a [memory](#) of having been that person. The new person will have all of the [patterns](#) of [knowledge](#), skill, and personality of the original. We are already creating functionally equivalent recreations of [neurons](#) and [neuron](#) clusters with sufficient accuracy that [biological neurons](#) accept their [nonbiological](#) equivalents and work with them as if they were [biological](#). There are no natural limits that prevent us from doing the same with the hundred billion [neuron](#) cluster of clusters we call the [human brain](#).

Subjectively, the issue is more subtle and profound, but first we need to reflect on one additional [objective](#) issue: our physical self.

The [Importance](#) of Having a Body

Consider how many of our [thoughts](#) and [thinking](#) are directed toward our body and its survival, security, nutrition, and image, not to mention affection, sexuality, and reproduction. Many, if not most, of the goals we attempt to advance using our brains have to do with our bodies: protecting them, providing them with fuel, making them attractive, making them feel good, providing for their myriad needs and desires. Some philosophers maintain that achieving [human](#) level [intelligence](#) is impossible without a body. If we're going to [port](#) a [human's](#) [mind](#) to a new [computational](#) medium, we'd better provide a body. A disembodied [mind](#) will quickly get depressed.

There are a variety of bodies that we will provide for our [machines](#), and that they will provide for themselves: bodies built through [nanotechnology](#) (i.e., building highly

complex physical [systems atom by atom](#)), virtual bodies (that exist only in [virtual reality](#)), bodies comprised of swarms of [nanobots](#), and other technologies.

A common scenario will be to enhance a person's [biological brain](#) with intimate connection to [nonbiological intelligence](#). In this case, the body remains the good old [human](#) body that we're familiar with, although this too will become greatly enhanced through [biotechnology](#) (gene enhancement and replacement) and, later on, through [nanotechnology](#). A detailed examination of twenty-first century bodies is beyond the scope of this essay, but recreating and enhancing our bodies will be (and has been) an easier task than recreating our minds.

So Just Who Are These People?

To return to the issue of subjectivity, consider: is the reinstated [mind](#) the same [consciousness](#) as the person we just scanned? Are these "people" conscious at all? Is this a [mind](#) or just a brain?

[Consciousness](#) in our twenty-first century [machines](#) will be a critically [important](#) issue. But it is not easily resolved, or even readily understood. People tend to have strong views on the subject, and often just can't understand how anyone else could possibly see the issue from a different perspective. [Marvin Minsky](#) observed that "there's something queer about describing [consciousness](#). Whatever people mean to say, they just can't seem to make it clear."

We don't worry, at least not yet, about causing pain and suffering to our [computer programs](#). But at what point do we consider an [entity](#), a process, to be conscious, to feel pain and discomfort, to have its own intentionality, its own [free will](#)? How do we determine if an [entity](#) is conscious; if it has [subjective experience](#)? How do we distinguish a process that is conscious from one that just acts *as if* it is conscious?

We can't simply ask it. If it says "Hey I'm conscious," does that settle the issue? No, we have [computer](#) games today that effectively do that, and they're not terribly convincing.

How about if the [entity](#) *is* very convincing and compelling when it says "I'm lonely, please keep me company." Does that settle the issue?

If we look inside its [circuits](#), and see essentially the identical kinds of feedback loops and other mechanisms in its [brain](#) that we see in a [human brain](#) (albeit [implemented](#) using [nonbiological](#) equivalents), does that settle the issue?

And just who are these people in the [machine](#), anyway? The answer will depend on who you ask. If you ask the people in the [machine](#), they will strenuously claim to be the original persons. For example, if we scan--let's say myself--and record the exact state, level, and position of every [neurotransmitter](#), [synapse](#), neural connection, and every other relevant detail, and then reinstantiate this massive [data](#) base of [information](#) (which I estimate at thousands of trillions of bytes) into a [neural computer](#) of sufficient [capacity](#),

the person who then emerges in the [machine](#) will think that "he" is (and had been) me, or at least he will act that way. He will say "I grew up in Queens, New York, went to college at MIT, stayed in the Boston area, started and sold a few [artificial intelligence](#) companies, walked into a scanner there, and woke up in the [machine](#) here. Hey, this [technology](#) really works."

But wait.

Is this really me? For one thing, old [biological](#) Ray (that's me) still exists. I'll still be here in my [carbon-cell](#)-based [brain](#). Alas, I will have to sit back and watch the new Ray succeed in endeavors that I could only [dream](#) of.

A Thought Experiment

Let's consider the issue of just who I am, and who the new Ray is a little more carefully. First of all, am I the stuff in my [brain](#) and body?

Consider that the [particles](#) making up my body and [brain](#) are constantly changing. We are not at all permanent collections of [particles](#). The cells in our bodies turn over at different rates, but the [particles](#) (e.g., atoms and [molecules](#)) that comprise our cells are exchanged at a very rapid rate. I am just not the same collection of [particles](#) that I was even a month ago. It is the [patterns](#) of [matter](#) and [energy](#) that are semipermanent (that is, changing only gradually), but our actual material [content](#) is changing constantly, and very quickly. We are rather like the [patterns](#) that water makes in a stream. The rushing water around a formation of rocks makes a particular, unique [pattern](#). This [pattern](#) may remain relatively unchanged for hours, even years. Of course, the actual material constituting the [pattern](#)--the water--is replaced in milliseconds. The same is true for [Ray Kurzweil](#). Like the water in a stream, my [particles](#) are constantly changing, but the [pattern](#) that people recognize as Ray has a [reasonable](#) level of continuity. This argues that we should not associate our fundamental [identity](#) with a specific [set](#) of [particles](#), but rather the [pattern](#) of [matter](#) and [energy](#) that we represent. Many contemporary philosophers seem partial to this "identify from [pattern](#)" argument.

But (again) wait.

If you were to scan my [brain](#) and reconstitute new Ray while I was sleeping, I would not necessarily even know about it (with the [nanobots](#), this will be a feasible scenario). If you then come to me, and say, "good news, Ray, we've successfully reconstituted your [mind file](#), so we won't be needing your old [brain](#) anymore," I may suddenly realize the flaw in this "identity from [pattern](#)" argument. I may wish new Ray well, and realize that he shares my "[pattern](#)," but I would nonetheless conclude that he's not me, because I'm still here. How could he be me? After all, I would not necessarily know that he even existed.

Let's consider another perplexing scenario. Suppose I replace a small [number](#) of [biological neurons](#) with functionally equivalent [nonbiological](#) ones (they may provide certain benefits such as greater reliability and longevity, but that's not relevant to this

[thought experiment](#)). After I have this procedure performed, am I still the same person? My friends certainly think so. I still have the same self-deprecating [humor](#), the same silly grin--yes, I'm still the same guy.

It should be clear where I'm going with this. [Bit](#) by [bit](#), region by region, I ultimately replace my entire [brain](#) with essentially identical (perhaps improved) [nonbiological](#) equivalents (preserving all of the [neurotransmitter](#) concentrations and other details that represent my [learning](#), skills, and memories). At each point, I feel the procedures were successful. At each point, I feel that I am the same guy. After each procedure, I claim to be the same guy. My friends concur. There is no old Ray and new Ray, just one Ray, one that never appears to fundamentally change.

But consider this. This gradual replacement of my [brain](#) with a [nonbiological](#) equivalent is essentially identical to the following sequence:

1. (i) scan Ray and reconstitute Ray's [mind file](#) into new ([nonbiological](#)) Ray, and, then
2. (ii) terminate old Ray. But we concluded above that in such a scenario new Ray is not the same as old Ray. And if old Ray is terminated, well then that's the end of Ray. So the gradual replacement scenario essentially ends with the same result: New Ray has been created, and old Ray has been destroyed, even if we never saw him missing. So what appears to be the continuing [existence](#) of just one Ray is really the creation of new Ray and the termination of old Ray.

On yet another hand (we're running out of philosophical hands here), the gradual replacement scenario is not altogether different from what happens normally to our [biological](#) selves, in that our [particles](#) are always rapidly being replaced. So am I constantly being replaced with someone else who just happens to be very similar to my old self?

I am trying to illustrate why [consciousness](#) is not an easy issue. If we talk about [consciousness](#) as just a certain type of intelligent skill: the ability to reflect on one's own self and situation, for example, then the issue is not difficult at all because any skill or capability or form of [intelligence](#) that one cares to define will be replicated in [nonbiological](#) entities (i.e., [machines](#)) within a few decades. With this type of *objective* view of [consciousness](#), the conundrums do go away. But a fully *objective* view does not penetrate to the core of the issue, because the essence of [consciousness](#) is *subjective experience*, not *objective* correlates of that [experience](#).

Will these [future machines](#) be capable of having [spiritual experiences](#)?

They certainly will claim to. They will claim to be people, and to have the full range of [emotional](#) and [spiritual experiences](#) that people claim to have. And these will not be idle claims; they will evidence the sort of rich, complex, and subtle behavior one associates with these feelings. How do the claims and behaviors--compelling as they will be--relate

to the [subjective experience](#) of these reinstated people? We keep coming back to the very real but ultimately unmeasurable issue of [consciousness](#).

People often talk about [consciousness](#) as if it were a clear property of an [entity](#) that can readily be identified, detected, and gauged. If there is one crucial insight that we can make regarding why the issue of [consciousness](#) is so [contentious](#), it is the following:

There exists no [objective](#) test that can conclusively determine its presence.

[Science](#) is about [objective](#) measurement and logical implications therefrom, but the very [nature](#) of [objectivity](#) is that you cannot measure [subjective experience](#)-you can only measure correlates of it, such as behavior (and by behavior, I include the [actions](#) of [components](#) of an [entity](#), such as [neurons](#)). This limitation has to do with the very [nature](#) of the [concepts](#) "[objective](#)" and "[subjective](#)." Fundamentally, we cannot penetrate the [subjective experience](#) of another [entity](#) with direct [objective](#) measurement. We can certainly make arguments about it: i.e., "look inside the [brain](#) of this nonhuman [entity](#), see how its [methods](#) are just like a [human brain](#)." Or, "see how its behavior is just like [human](#) behavior." But in the end, these remain just arguments. No [matter](#) how convincing the behavior of a reinstated person, some observers will refuse to accept the [consciousness](#) of an [entity](#) unless it squirts [neurotransmitters](#), or is based on [DNA](#)-guided [protein synthesis](#), or has some other specific [biologically human attribute](#).

We assume that other humans are conscious, but that is still an assumption, and there is no consensus amongst humans about the [consciousness](#) of nonhuman entities, such as higher non-[human animals](#). The issue will be even more [contentious](#) with regard to [future nonbiological](#) entities with [human](#)-like behavior and [intelligence](#).

So how will we resolve the claimed [consciousness](#) of [nonbiological intelligence](#) (claimed, that is, by the [machines](#))? From a practical perspective, we'll accept their claims. Keep in [mind](#) that [nonbiological](#) entities in the twenty-first century will be extremely intelligent, so they'll be able to convince us that they are conscious. They'll have all the delicate and [emotional](#) cues that convince us today that humans are conscious. They will be able to make us laugh and cry. And they'll get mad if we don't accept their claims. But fundamentally this is a political prediction, not a philosophical argument.

On Tubules and [Quantum Computing](#)

Over the past several years, [Roger Penrose](#), a noted physicist and philosopher, has suggested that fine [structures](#) in the [neurons](#) called tubules perform an exotic form of [computation](#) called "[quantum computing](#)." [Quantum computing](#) is computing using what are called "qu bits" which take on all possible combinations of solutions simultaneously. It can be considered to be an extreme form of [parallel processing](#) (because every combination of values of the qu bits are tested simultaneously). Penrose suggests that the tubules and their [quantum computing](#) capabilities complicate the [concept](#) of recreating [neurons](#) and reinstating [mind files](#).

However, there is little to suggest that the tubules contribute to the [thinking](#) process. Even generous models of [human knowledge](#) and capability are more than accounted for by current estimates of [brain](#) size, based on contemporary models of [neuron](#) functioning that do not include tubules. In fact, even with these tubule-less models, it appears that the [brain](#) is conservatively designed with many more connections (by several orders of magnitude) than it needs for its capabilities and [capacity](#). Recent [experiments](#) (e.g., the San Diego Institute for Nonlinear [Science experiments](#)) showing that hybrid [biological-nonbiological networks](#) perform similarly to all [biological networks](#), while not definitive, are strongly suggestive that our tubule-less models of [neuron](#) functioning are adequate. [Lloyd Watts' software](#) simulation of his intricate model of [human](#) auditory processing uses orders of magnitude less [computation](#) than the [networks](#) of [neurons](#) he is simulating, and there is no suggestion that [quantum computing](#) is needed.

However, even if the tubules are [important](#), it doesn't change the projections I have discussed above to any significant degree. According to my model of [computational growth](#), if the tubules multiplied [neuron complexity](#) by a factor of a thousand (and keep in [mind](#) that our current tubule-less [neuron](#) models are already complex, including on the [order](#) of a thousand connections per [neuron](#), multiple nonlinearities and other details), this would delay our reaching [brain capacity](#) by only about 9 years. If we're off by a factor of a million, that's still only a delay of 17 years. A factor of a billion is around 24 years (keep in [mind](#) [computation](#) is growing by a double exponential).

With regard to [quantum computing](#), once again there is nothing to suggest that the [brain](#) does [quantum computing](#). Just because quantum [technology](#) may be feasible does not suggest that the [brain](#) is capable of it. After all, we don't have lasers or even radios in our brains. Although some scientists have claimed to detect quantum [wave](#) collapse in the [brain](#), no one has suggested [human](#) capabilities that actually require a [capacity](#) for [quantum computing](#).

However, even if the [brain](#) does do [quantum computing](#), this does not significantly change the outlook for [human-level](#) computing (and beyond) nor does it suggest that [brain downloading](#) is infeasible. First of all, if the [brain](#) does do [quantum computing](#) this would only verify that [quantum computing](#) is feasible. There would be nothing in such a finding to suggest that [quantum computing](#) is restricted to [biological](#) mechanisms. [Biological quantum computing](#) mechanisms, if they exist, could be replicated. Indeed, recent [experiments](#) with small scale quantum [computers](#) appear to be successful. Even the conventional [transistor](#) relies on the quantum effect of [electron tunneling](#).

Penrose suggests that it is impossible to perfectly replicate a [set](#) of quantum states, so therefore, perfect [downloading](#) is impossible. Well, how perfect does a [download](#) have to be? I am at this moment in a very different quantum state (and different in non-quantum ways as well) than I was a minute ago (certainly in a very different state than I was before I wrote this paragraph). If we develop [downloading technology](#) to the point where the "copies" are as close to the original as the original person changes anyway in the course of one minute, that would be good enough for any conceivable purpose, yet does not require copying quantum states. As the [technology](#) improves, the accuracy of the copy

could become as close as the original changes within ever briefer periods of [time](#) (e.g., one second, one millisecond, one microsecond).

When it was pointed out to Penrose that [neurons](#) (and even neural connections) were too big for [quantum computing](#), he came up with the tubule theory as a possible mechanism for neural [quantum computing](#). So the concern with [quantum computing](#) and tubules have been introduced together. If one is [searching](#) for barriers to replicating [brain](#) function, it is an ingenious theory, but it fails to introduce any genuine barriers. There is no evidence for it, and even if true, it only delays [matters](#) by a decade or two. There is no [reason](#) to believe that [biological](#) mechanisms (including [quantum computing](#)) are inherently impossible to replicate using [nonbiological](#) materials and mechanisms. Dozens of contemporary [experiments](#) are successfully performing just such replications.

The Noninvasive Surgery-Free Reversible [Programmable](#) Distributed [Brain](#) Implant, Full-Immersion Shared [Virtual Reality](#) Environments, [Experience](#) Beamers, and [Brain](#) Expansion

How will we apply [technology](#) that is more intelligent than its creators? One might be tempted to respond "Carefully!" But let's take a look at some examples.

Consider several examples of the [nanobot technology](#), which, based on [miniaturization](#) and cost [reduction](#) trends, will be feasible within 30 years. In addition to scanning your [brain](#), the [nanobots](#) will also be able to expand our [experiences](#) and our capabilities.

[Nanobot technology](#) will provide fully immersive, totally convincing [virtual reality](#) in the following way. The [nanobots](#) take up positions in close physical proximity to every interneuronal connection coming from all of our senses (e.g., eyes, ears, skin). We already have the [technology](#) for [electronic devices](#) to communicate with [neurons](#) in both directions that requires no direct physical contact with the [neurons](#). For example, scientists at the [Max Planck](#) Institute have developed "[neuron transistors](#)" that can detect the firing of a nearby [neuron](#), or alternatively, can cause a nearby [neuron](#) to fire, or suppress it from firing. This amounts to two-way [communication](#) between [neurons](#) and the [electronic](#)-based [neuron transistors](#). The Institute scientists demonstrated their [invention](#) by controlling the movement of a living leech from their [computer](#). Again, the primary aspect of [nanobot](#)-based [virtual reality](#) that is not yet feasible is size and cost.

When we want to [experience](#) real [reality](#), the [nanobots](#) just stay in position (in the capillaries) and do nothing. If we want to enter [virtual reality](#), they suppress all of the inputs coming from the real senses, and replace them with the signals that would be appropriate for the virtual environment. You (i.e., your [brain](#)) could decide to cause your muscles and limbs to move as you normally would, but the [nanobots](#) again intercept these interneuronal signals, suppress your real limbs from moving, and instead cause your

virtual limbs to move and provide the appropriate movement and reorientation in the virtual environment.

The web will provide a panoply of virtual environments to explore. Some will be recreations of real places, others will be fanciful environments that have no "real" counterpart. Some indeed would be impossible in the physical world (perhaps, because they violate the laws of [physics](#)). We will be able to "go" to these virtual environments by ourselves, or we will meet other people there, both real people and simulated people. Of course, ultimately there won't be a clear distinction between the two.

By 2030, going to a web site will mean entering a full immersion [virtual reality](#) environment. In addition to encompassing all of the senses, these shared environments can include [emotional](#) overlays as the [nanobots](#) will be capable of triggering the neurological correlates of [emotion](#)s, sexual pleasure, and other derivatives of our sensory [experience](#) and mental reactions.

In the same way that people today beam their lives from web cams in their bedrooms, "[experience](#) beamers" circa 2030 will beam their entire flow of sensory [experiences](#), and if so desired, their [emotion](#)s and other secondary reactions. We'll be able to plug in (by going to the appropriate web site) and [experience](#) other people's lives as in the plot [concept](#) of 'Being John Malkovich.' Particularly interesting [experiences](#) can be archived and relived at any [time](#).

We won't need to wait until 2030 to [experience](#) shared [virtual reality](#) environments, at least for the visual and auditory senses. Full immersion visual-auditory environments will be available by the end of this decade with images written directly onto our [retinas](#) by our eyeglasses and contact lenses. All of the [electronics](#) for the [computation](#), image reconstruction, and very high [bandwidth wireless](#) connection to the [Internet](#) will be embedded in our glasses and woven into our clothing, so [computers](#) as distinct [objects](#) will disappear.

In my view, the most significant implication of the [Singularity](#) will be the merger of [biological](#) and [nonbiological intelligence](#). First, it is [important](#) to point out that well before the end of the twenty-first century, [thinking](#) on [nonbiological substrates](#) will dominate. [Biological thinking](#) is stuck at 10^{26} calculations per second (for all [biological human](#) brains), and that figure will not appreciably change, even with [bioengineering](#) changes to our [genome](#). [Nonbiological intelligence](#), on the other hand, is growing at a double exponential rate and will vastly exceed [biological intelligence](#) well before the middle of this century. However, in my view, this [nonbiological intelligence](#) should still be considered [human](#) as it is fully derivative of the [human-machine civilization](#). The merger of these two worlds of [intelligence](#) is not merely a merger of [biological](#) and [nonbiological thinking](#) mediums, but more [importantly](#) one of [method](#) and organization of [thinking](#).

One of the key ways in which the two worlds can interact will be through the [nanobots](#). [Nanobot technology](#) will be able to expand our minds in virtually any imaginable way.

Our brains today are relatively fixed in design. Although we do add [patterns](#) of interneuronal connections and [neurotransmitter](#) concentrations as a normal part of the [learning](#) process, the current overall [capacity](#) of the [human brain](#) is highly constrained, restricted to a mere hundred trillion connections. [Brain](#) implants based on massively distributed intelligent [nanobots](#) will ultimately expand our memories a trillion fold, and otherwise vastly improve all of our sensory, [pattern recognition](#), and cognitive abilities. Since the [nanobots](#) are communicating with each other over a [wireless local area network](#), they can create any [set](#) of new neural connections, can break existing connections (by suppressing neural firing), can create new hybrid [biological-nonbiological networks](#), as well as add vast new [nonbiological networks](#).

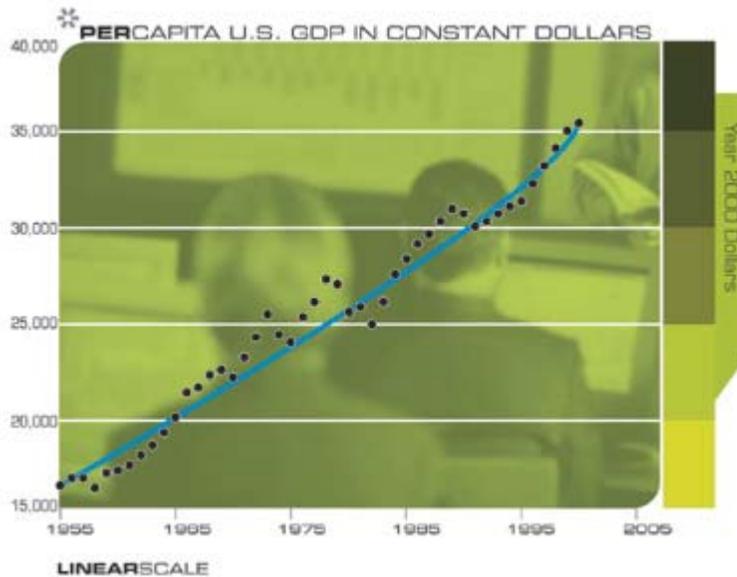
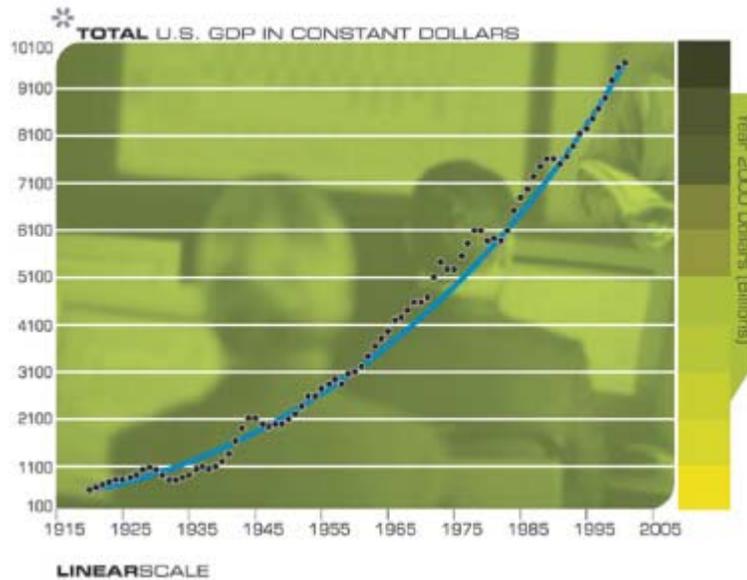
Using [nanobots](#) as [brain](#) extenders is a significant improvement over the idea of surgically installed [neural implants](#), which are beginning to be used today (e.g., ventral posterior [nucleus](#), subthalamic [nucleus](#), and ventral lateral thalamus [neural implants](#) to counteract [Parkinson's Disease](#) and tremors from other neurological disorders, [cochlear implants](#), and others.) [Nanobots](#) will be introduced without surgery, essentially just by injecting or even swallowing them. They can all be directed to leave, so the process is easily reversible. They are [programmable](#), in that they can provide [virtual reality](#) one minute, and a variety of [brain](#) extensions the next. They can change their [configuration](#), and clearly can alter their [software](#). Perhaps most [importantly](#), they are massively distributed and therefore can take up billions or trillions of positions throughout the [brain](#), whereas a surgically introduced [neural implant](#) can only be placed in one or at most a few locations.

The Double [Exponential Growth](#) of the Economy During the 1990s Was Not a Bubble

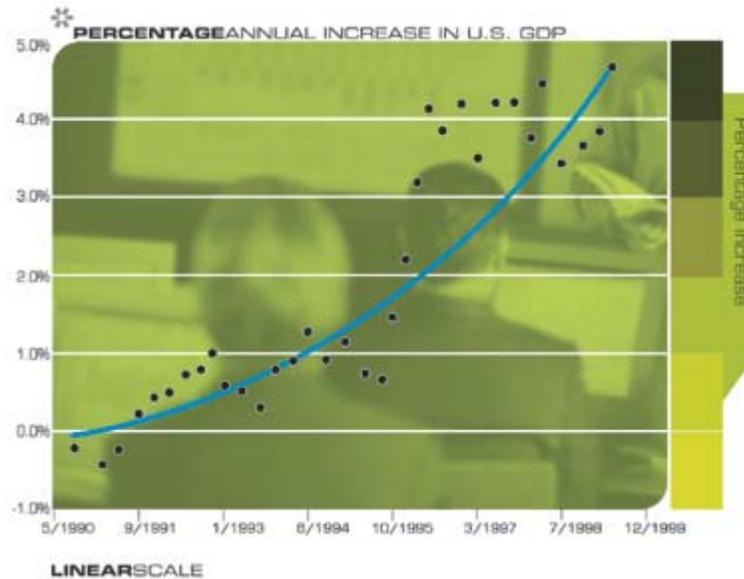
Yet another manifestation of the [law of accelerating returns](#) as it rushes toward the [Singularity](#) can be found in the world of [economics](#), a world vital to both the genesis of the [law of accelerating returns](#), and to its implications. It is the economic imperative of a competitive marketplace that is driving [technology](#) forward and fueling the [law of accelerating returns](#). In turn, the [law of accelerating returns](#), particularly as it approaches the [Singularity](#), is transforming economic relationships.

Virtually all of the economic models taught in [economics](#) classes, used by the Federal Reserve Board to [set](#) monetary policy, by [Government](#) agencies to [set](#) economic policy, and by economic forecasters of all kinds are fundamentally flawed because they are based on the [intuitive linear view](#) of [history](#) rather than the historically based exponential view. The [reason](#) that these [linear](#) models appear to work for a while is for the same [reason](#) that most people adopt the [intuitive linear view](#) in the first place: [exponential trends](#) appear to be [linear](#) when viewed (and [experienced](#)) for a brief period of [time](#), particularly in the early stages of an [exponential trend](#) when not much is happening. But once the "[knee of the curve](#)" is achieved and the [exponential growth](#) explodes, the [linear](#) models break down. The [exponential trends](#) underlying [productivity growth](#) are just beginning this explosive phase.

The economy (viewed either in total or per capita) has been growing exponentially throughout this century:



There is also a second level of [exponential growth](#), but up until recently the second exponent has been in the early phase so that the [growth](#) in the [growth](#) rate has not been noticed. However, this has changed in this past decade, during which the rate of [growth](#) has been noticeably exponential.

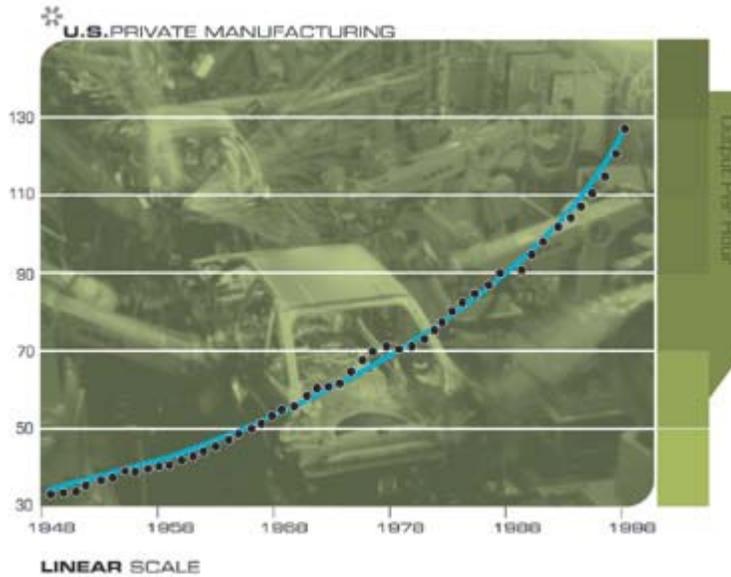


[Productivity](#) (economic output per worker) has also been growing exponentially. Even these statistics are greatly understated because they do not fully reflect significant improvements in the quality and features of products and services. It is not the case that "a car is a car;" there have been significant improvements in safety, reliability, and features. There are a myriad of such examples. [Pharmaceutical](#) drugs are increasingly effective. Groceries ordered in five minutes on the web and delivered to your door are worth more than groceries on a supermarket shelf that you have to fetch yourself. Clothes custom manufactured for your unique [body scan](#) are worth more than clothes you happen to find left on a store rack. These sorts of improvements are true for most product categories, and none of them are reflected in the [productivity](#) statistics.

The statistical [methods](#) underlying the [productivity](#) measurements tend to factor out gains by essentially concluding that we still only get one dollar of products and services for a dollar despite the fact that we get much more for a dollar (e.g., compare a \$1,000 [computer](#) today to one ten years ago). University of Chicago Professor Pete Klenow and University of Rochester Professor Mark Bils estimate that the value of existing goods has been increasing at 1.5% per year for the past 20 years because of qualitative improvements. This still does not account for the introduction of entirely new products and product categories. The [Bureau of Labor Statistics](#), which is responsible for the [inflation](#) statistics, uses a model that incorporates an estimate of quality [growth](#) at only 0.5% per year, reflecting a [systematic](#) underestimate of quality improvement and a resulting overestimate of [inflation](#) by at least 1 percent per year.

Despite these weaknesses in the [productivity](#) statistical [methods](#), the gains in [productivity](#) are now reaching the steep part of the exponential curve. Labor [productivity](#) grew at 1.6% per year until 1994, then rose at 2.4% per year, and is now growing even more rapidly. In the quarter ending July 30, 2000, labor [productivity](#) grew at 5.3%. Manufacturing [productivity](#) grew at 4.4% annually from 1995 to 1999, durables manufacturing at 6.5%

per year.



The 1990s have seen the most powerful deflationary forces in [history](#). This is why we are not seeing [inflation](#). Yes, it's true that low unemployment, high asset values, economic [growth](#), and other such factors are [inflationary](#), but these factors are offset by the double [exponential trends](#) in the [price-performance](#) of all [information](#) based technologies: [computation](#), [memory](#), [communications](#), [biotechnology](#), [miniaturization](#), and even the overall rate of technical [progress](#). These technologies deeply affect all industries.

We are also undergoing massive [disintermediation](#) in the channels of distribution through the web and other new [communication](#) technologies, as well as escalating efficiencies in [operations](#) and administration.

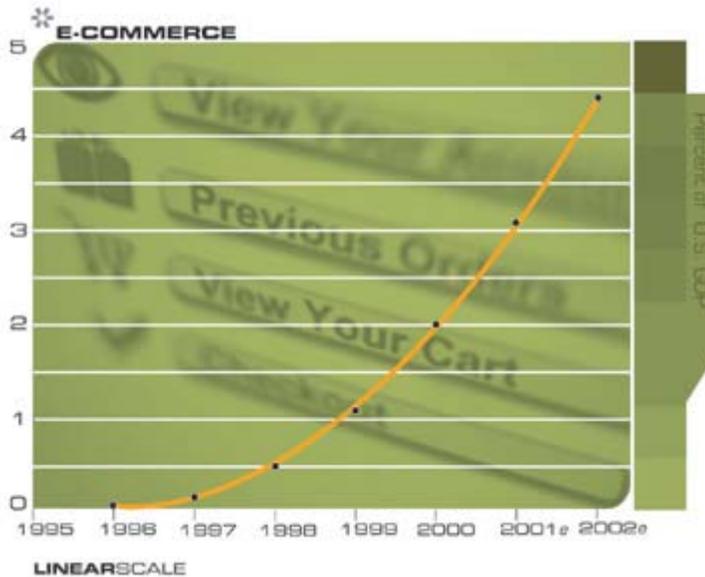
All of the [technology](#) trend charts in this essay represent massive deflation. There are many examples of the impact of these escalating efficiencies. BP Amoco's cost for finding oil is now less than \$1 per barrel, down from nearly \$10 in 1991. Processing an [internet](#) transaction costs a bank one penny, compared to over \$1 using a teller ten years ago. A Roland Berger / Deutsche Bank study estimates a cost savings of \$1200 per North American car over the next five years. A more optimistic Morgan Stanley study estimates that [Internet](#)-based procurement will save Ford, GM, and DaimlerChrysler about \$2700 per vehicle. [Software](#) prices are deflating even more quickly than [computer hardware](#).

Software Price-Performance Has Also Improved at an Exponential Rate

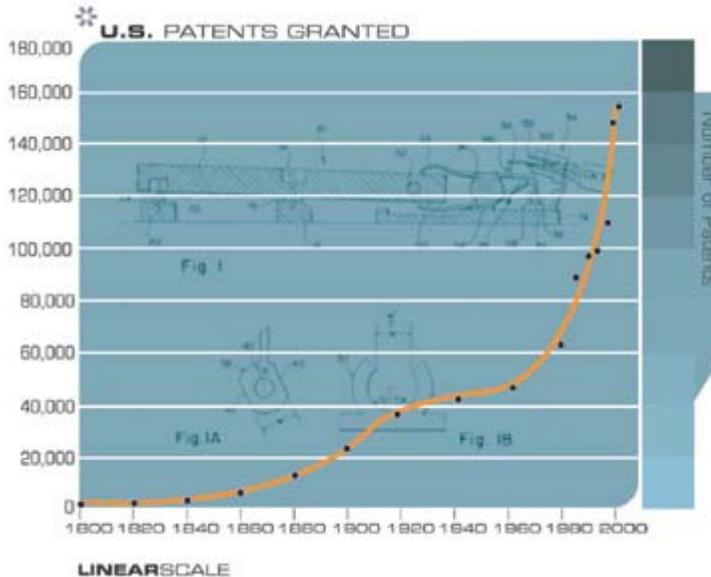
(Example: [Automatic Speech Recognition Software](#))

1985 1995 2000

Price	\$5,000	\$500	\$50
Vocabulary Size (# words)	1,000	10,000	100,000
Continuous Speech?	No	No	Yes
User Training Required (Minutes)	180	60	5
Accuracy	Poor	Fair	Good



Current economic policy is based on outdated models which include [energy](#) prices, commodity prices, and capital investment in plant and equipment as key driving factors, but do not adequately model [bandwidth](#), [MIPs](#), megabytes, [intellectual property](#), [knowledge](#), and other increasingly vital (and increasingly increasing) constituents that are driving the economy.



The economy "wants" to grow more than the 3.5% per year, which constitutes the current "speed limit" that the Federal Reserve bank and other policy makers have established as "safe," meaning noninflationary. But in keeping with the [law of accelerating returns](#), the economy is capable of "safely" establishing this level of [growth](#) in less than a year, implying a [growth](#) rate in an entire year of greater than 3.5%. Recently, the [growth](#) rate has exceeded 5%.

None of this means that cycles of recession will disappear immediately. The economy still has some of the underlying [dynamics](#) that historically have caused cycles of recession, specifically excessive commitments such as capital intensive projects and the overstocking of [inventories](#). However, the rapid dissemination of [information](#), sophisticated forms of online procurement, and increasingly transparent markets in all industries have diminished the impact of this cycle. So "recessions" are likely to be shallow and short lived. The underlying long-term [growth](#) rate will continue at a double exponential rate.

The overall [growth](#) of the economy reflects completely new forms and layers of [wealth](#) and value that did not previously exist, or least that did not previously constitute a significant portion of the economy (but do now): [intellectual property](#), [communication portals](#), web sites, [bandwidth](#), [software](#), [data](#) bases, and many other new [technology](#) based categories.

There is no need for high interest rates to counter an [inflation](#) that doesn't exist. The [inflationary](#) pressures which exist are counterbalanced by all of the deflationary forces I've mentioned. The current high interest rates fostered by the Federal Reserve Bank are destructive, are causing trillions of dollars of lost [wealth](#), are regressive, hurt business and the middle class, and are completely unnecessary.

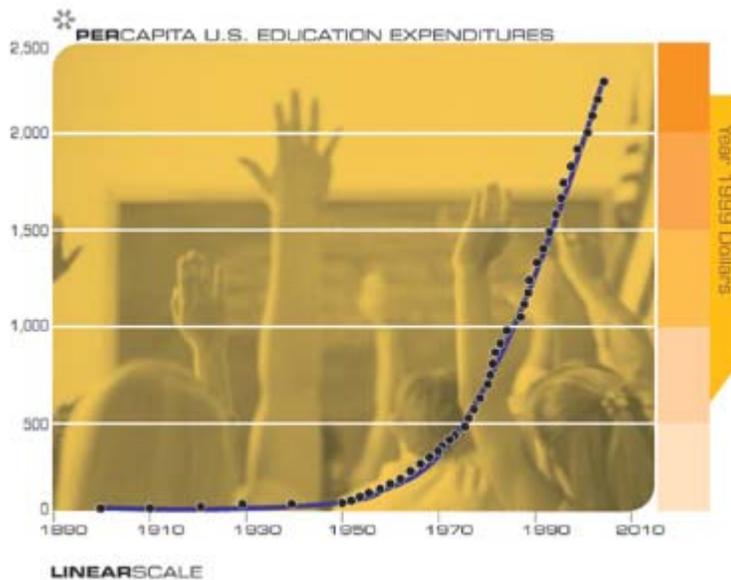
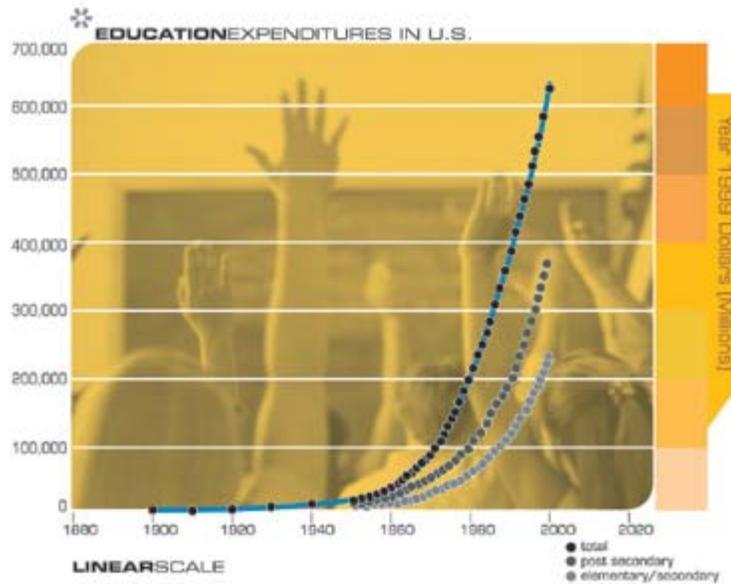
The Fed's monetary policy is only influential because people believe it to be. It has little real power. The economy today is largely backed by private capital in the form of a growing variety of equity [instruments](#). The portion of available liquidity in the economy that the Fed actually controls is relatively insignificant. The reserves that banks and financial institutions maintain with the Federal Reserve [System](#) are less than \$50 billion, which is only 0.6% of the [GDP](#), and 0.25% of the liquidity available in stocks.

Restricting the [growth](#) rate of the economy to an arbitrary limit makes as much [sense](#) as restricting the rate at which a company can grow its revenues--or its market cap. Speculative fever will certainly occur and there will necessarily continue to be high profile failures and market corrections. However the ability of [technology](#) companies to rapidly create new--real--[wealth](#) is just one of the factors that will continue to fuel ongoing double [exponential growth](#) in the economy. These policies have led to an "[Alice in Wonderland](#)" situation in which the market goes up on bad economic news (because it means that more unnecessary punishment will be avoided) and goes down on good economic news.

Speaking of market speculative fever and market corrections, the stock market values for so-called "B to B" ([Business to Business](#)) and "B to [C](#)" ([Business to Consumer](#)) web [portals](#) and enabling technologies is likely to come back strongly as it becomes clear that economic transactions are indeed escalating toward [e-commerce](#), and that the (surviving) contenders are capable of demonstrating profitable business models.

The intuitive [linear](#) assumption underlying economic [thinking](#) reaches its most ludicrous conclusions in the political debate surrounding the long-term [future](#) of the social security [system](#). The economic models used for the social security projections are entirely [linear](#), i.e., they reflect fixed economic [growth](#). This might be viewed as conservative planning if we were talking about projections of only a few years, but they become utterly unrealistic for the three to four decades being discussed. These projections actually assume a fixed rate of [growth](#) of 3.5% per year for the next fifty years! There are incredibly naïve assumptions that bear on both sides of the argument. On the one hand, there will be radical extensions to [human](#) longevity, while on the other hand, we will benefit from far greater economic expansion. These factors do not rule each other out, however, as the positive factors are stronger, and will ultimately dominate. Moreover, we are certain to rethink social security when we have centenarians who look and act like 30 year-olds (but who will think much faster than 30 year-olds circa the year 2000).

Another implication of the [law of accelerating returns](#) is [exponential growth](#) in [education](#) and [learning](#). Over the past 120 years, we have increased our investment in K-12 [education](#) (per student and in constant dollars) by a factor of ten. We have a one hundred fold increase in the [number](#) of college students. [Automation](#) started by amplifying the power of our muscles, and in recent times has been amplifying the power of our minds. Thus, for the past two centuries, [automation](#) has been eliminating jobs at the bottom of the skill ladder while creating new (and better paying) jobs at the top of the skill ladder. So the ladder has been moving up, and thus we have been exponentially increasing investments in [education](#) at all levels.



Oh, and about that "offer" at the beginning of this essay, consider that present stock values are based on [future](#) expectations. Given that the (literally) short sighted [linear](#) intuitive view represents the ubiquitous outlook, the common [wisdom](#) in economic expectations are dramatically understated. Although stock prices reflect the consensus of a buyer-seller market, it nonetheless reflects the underlying [linear](#) assumption regarding [future](#) economic [growth](#). But the [law of accelerating returns](#) clearly implies that the [growth](#) rate will continue to grow exponentially because the rate of [progress](#) will continue to accelerate. Although (weakening) recessionary cycles will continue to cause

immediate [growth](#) rates to fluctuate, the underlying rate of [growth](#) will continue to double approximately every decade.

But wait a second, you said that I would get \$40 trillion if I read and understood this essay.

That's right. According to my models, if we replace the [linear](#) outlook with the more appropriate exponential outlook, current stock prices should triple. Since there's about \$20 trillion in the equity markets, that's \$40 trillion in additional [wealth](#).

But you said I would get that money.

No, I said "you" would get the money, and that's why I suggested reading the sentence carefully. The English word "you" can be singular or plural. I meant it in the [sense](#) of "all of you."

I see, all of us as in the whole world. But not everyone will read this essay.

Well, but everyone could. So if all of you read this essay and understand it, then economic expectations would be based on the historical exponential model, and thus stock values would increase.

You mean if everyone understands it, and agrees with it.

Okay, I suppose I was assuming that.

Is that what you expect to happen.

Well, actually, no. Putting on my [futurist](#) hat again, my prediction is that indeed these views will prevail, but only over [time](#), as more and more evidence of the exponential [nature](#) of [technology](#) and its impact on the economy becomes apparent. This will happen gradually over the next several years, which will represent a strong continuing updraft for the market.

A Clear and [Future](#) Danger

[Technology](#) has always been a double edged sword, bringing us longer and healthier [life](#) spans, [freedom](#) from physical and mental drudgery, and many new creative possibilities on the one hand, while introducing new and [salient](#) dangers on the other. We still live today with sufficient nuclear [weapons](#) (not all of which appear to be well accounted for) to end all [mammalian life](#) on the [planet](#). [Bioengineering](#) is in the early stages of enormous strides in reversing [disease](#) and aging processes. However, the means and [knowledge](#) will soon exist in a routine college [bioengineering](#) lab (and already exists in more sophisticated labs) to create unfriendly [pathogens](#) more dangerous than nuclear [weapons](#). As [technology](#) accelerates toward the [Singularity](#), we will see the same intertwined

potentials: a feast of [creativity](#) resulting from [human intelligence](#) expanded a trillion-fold combined with many grave new dangers.

Consider unrestrained [nanobot](#) replication. [Nanobot technology](#) requires billions or trillions of such intelligent [devices](#) to be useful. The most cost effective way to scale up to such levels is through [self-replication](#), essentially the same approach used in the [biological](#) world. And in the same way that [biological self-replication](#) gone awry (i.e., [cancer](#)) results in [biological](#) destruction, a defect in the mechanism curtailing [nanobot self-replication](#) would endanger all physical entities, [biological](#) or otherwise.

Other primary concerns include "who is controlling the [nanobots](#)?" and "who are the [nanobots](#) talking to?" Organizations (e.g., [governments](#), extremist groups) or just a clever [individual](#) could put trillions of undetectable [nanobots](#) in the water or food supply of an [individual](#) or of an entire population. These "spy" [nanobots](#) could then monitor, influence, and even control our [thoughts](#) and [actions](#). In addition to introducing physical spy [nanobots](#), existing [nanobots](#) could be influenced through [software](#) viruses and other [software](#) "hacking" techniques. When there is [software](#) running in our brains, issues of [privacy](#) and security will take on a new urgency.

My own expectation is that the creative and constructive applications of this [technology](#) will dominate, as I believe they do today. But there will be a valuable (and increasingly vocal) role for a concerned and constructive Luddite movement (i.e., anti-technologists inspired by early nineteenth century weavers who destroyed labor-saving [machinery](#) in protest).

If we imagine describing the dangers that exist today to people who lived a couple of hundred years ago, they would think it mad to take such risks. On the other hand, how many people in the year 2000 would really want to go back to the short, brutish, [disease](#)-filled, [poverty](#)-stricken, disaster-prone lives that 99 percent of the [human](#) race struggled through a couple of centuries ago? We may romanticize the past, but up until fairly recently, most of humanity lived extremely fragile lives where one all too common misfortune could spell disaster. Substantial portions of our [species](#) still live in this precarious way, which is at least one [reason](#) to continue technological [progress](#) and the economic enhancement that accompanies it.

People often go through three stages in examining the impact of [future technology](#): awe and wonderment at its potential to overcome age old problems, then a [sense](#) of dread at a new [set](#) of grave dangers that accompany these new technologies, followed, finally and hopefully, by the realization that the only viable and responsible path is to [set](#) a careful course that can realize the promise while managing the peril.

In his cover story for [WIRED](#) *Why The [Future](#) Doesn't Need Us*, [Bill Joy](#) eloquently described the plagues of centuries' past, and how new self-replicating technologies, such as mutant bioengineered [pathogens](#), and "[nanobots](#)" run amok, may bring back long forgotten pestilence. Indeed these are real dangers. It is also the case, which Joy acknowledges, that it has been technological advances, such as [antibiotics](#) and improved

sanitation, which has freed us from the prevalence of such plagues. Suffering in the world continues and demands our steadfast attention. Should we tell the millions of people afflicted with [cancer](#) and other devastating conditions that we are canceling the development of all bioengineered treatments because there is a risk that these same technologies may someday be used for malevolent purposes? Having asked the rhetorical question, I realize that there is a movement to do exactly that, but I think most people would agree that such broad based [relinquishment](#) is not the answer.

The continued opportunity to alleviate [human](#) distress is one [important](#) motivation for continuing technological advancement. Also compelling are the already apparent economic gains I discussed above which will continue to hasten in the decades ahead. The continued acceleration of many intertwined technologies are roads paved with gold (I use the plural here because [technology](#) is clearly not a single path). In a competitive environment, it is an economic imperative to go down these roads. Relinquishing technological advancement would be economic suicide for [individuals](#), companies, and nations.

Which brings us to the issue of [relinquishment](#), which is [Bill Joy's](#) most controversial recommendation and personal commitment. I do feel that [relinquishment](#) at the right level is part of a responsible and constructive response to these genuine perils. The issue, however, is exactly this: at what level are we to relinquish [technology](#)?

[Ted Kaczynski](#) would have us renounce all of it. This, in my view, is neither desirable nor feasible, and the futility of such a position is only underscored by the senselessness of Kaczynski's deplorable tactics.

Another level would be to forego certain fields; [nanotechnology](#), for example, that might be regarded as too dangerous. But such sweeping strokes of [relinquishment](#) are equally untenable. [Nanotechnology](#) is simply the inevitable end result of the persistent trend toward [miniaturization](#) which pervades all of [technology](#). It is far from a single centralized effort, but is being pursued by a myriad of projects with many diverse goals.

One observer wrote:

"A further [reason](#) why industrial [society](#) cannot be reformed. . . is that modern [technology](#) is a unified [system](#) in which all parts are dependent on one another. You can't get rid of the "bad" parts of [technology](#) and retain only the "good" parts. Take modern [medicine](#), for example. [Progress](#) in medical [science](#) depends on [progress](#) in [chemistry](#), [physics](#), [biology](#), [computer science](#) and other fields. Advanced medical treatments require expensive, high-tech equipment that can be made available only by a technologically [progressive](#), economically rich [society](#). Clearly you can't have much [progress](#) in [medicine](#) without the whole technological [system](#) and everything that goes with it."

The observer I am quoting is, again, [Ted Kaczynski](#). Although one might properly resist Kaczynski as an authority, I believe he is correct on the deeply entangled [nature](#) of the benefits and risks. However, Kaczynski and I clearly part company on our overall

assessment on the relative balance between the two. [Bill Joy](#) and I have dialogued on this issue both publicly and privately, and we both believe that [technology](#) will and should [progress](#), and that we need to be actively concerned with the dark side. If Bill and I disagree, it's on the granularity of [relinquishment](#) that is both feasible and desirable.

Abandonment of broad areas of [technology](#) will only push them underground where development would continue unimpeded by [ethics](#) and regulation. In such a situation, it would be the less stable, less responsible practitioners (e.g., the terrorists) who would have all the expertise.

I do think that [relinquishment](#) at the right level needs to be part of our ethical response to the dangers of twenty first century technologies. One constructive example of this is the proposed ethical guideline by the [Foresight Institute](#), founded by [nanotechnology](#) pioneer Eric Drexler, that [nanotechnologists](#) agree to relinquish the development of physical entities that can self-replicate in a natural environment. Another is a ban on self-replicating physical entities that contain their own codes for [self-replication](#). In what [nanotechnologist](#) Ralph Merkle calls the "[Broadcast Architecture](#)," such entities would have to obtain such codes from a centralized secure [server](#), which would guard against undesirable replication. The [Broadcast Architecture](#) is impossible in the [biological](#) world, which represents at least one way in which [nanotechnology](#) can be made safer than [biotechnology](#). In other ways, [nanotech](#) is potentially more dangerous because [nanobots](#) can be physically stronger than [protein](#)-based entities and more intelligent. It will eventually be possible to combine the two by having [nanotechnology](#) provide the codes within [biological](#) entities (replacing [DNA](#)), in which case [biological](#) entities can use the much safer [Broadcast Architecture](#).

Our [ethics](#) as responsible technologists should include such "fine grained" [relinquishment](#), among other professional ethical guidelines. Other protections will need to include oversight by regulatory bodies, the development of [technology](#)-specific "immune" responses, as well as [computer](#) assisted surveillance by law enforcement organizations. Many people are not aware that our [intelligence](#) agencies already use advanced technologies such as automated word spotting to monitor a substantial flow of telephone [conversation](#)s. As we go forward, balancing our cherished rights of [privacy](#) with our need to be protected from the malicious use of powerful twenty first century technologies will be one of many profound challenges. This is one [reason](#) that such issues as an [encryption](#) "trap door" (in which law enforcement authorities would have [access](#) to otherwise secure [information](#)) and the FBI "[Carnivore](#)" [email](#)-snooping [system](#) have been so [contentious](#).

As a test case, we can take a small measure of comfort from how we have dealt with one recent technological challenge. There exists today a new form of fully [nonbiological](#) self replicating [entity](#) that didn't exist just a few decades ago: the [computer virus](#). When this form of destructive intruder first appeared, strong concerns were voiced that as they became more sophisticated, [software pathogens](#) had the potential to destroy the [computer network](#) medium they live in. Yet the "[immune system](#)" that has evolved in response to this challenge has been largely effective. Although destructive self-replicating [software](#)

entities do cause damage from [time](#) to [time](#), the injury is but a small fraction of the benefit we receive from the [computers](#) and [communication](#) links that harbor them. No one would suggest we do away with [computers](#), [local area networks](#), and the [Internet](#) because of [software](#) viruses.

One might counter that [computer](#) viruses do not have the lethal potential of [biological](#) viruses or of destructive [nanotechnology](#). Although true, this strengthens my observation. The fact that [computer](#) viruses are not usually deadly to humans only means that more people are willing to create and release them. It also means that our response to the danger is that much less intense. Conversely, when it comes to self replicating entities that are potentially lethal on a large scale, our response on all levels will be vastly more serious.

[Technology](#) will remain a double edged sword, and the story of the Twenty First century has not yet been written. It represents vast power to be used for all humankind's purposes. We have no choice but to work hard to apply these quickening technologies to advance our [human](#) values, despite what often appears to be a lack of consensus on what those values should be.

Living Forever

Once [brain](#) porting [technology](#) has been refined and fully developed, will this enable us to live forever? The answer depends on what we mean by living and dying. Consider what we do today with our [personal computer](#) files. When we change from one [personal computer](#) to a less obsolete model, we don't throw all our files away; rather we copy them over to the new [hardware](#). Although our [software](#) files do not necessarily continue their [existence](#) forever, the longevity of our [personal computer software](#) is completely separate and disconnected from the [hardware](#) that it runs on. When it comes to our personal [mind file](#), however, when our [human hardware](#) crashes, the [software](#) of our lives dies with it. However, this will not continue to be the case when we have the means to store and restore the thousands of trillions of bytes of [information](#) represented in the [pattern](#) that we call our brains.

The longevity of one's [mind file](#) will not be dependent, therefore, on the continued viability of any particular [hardware](#) medium. Ultimately [software](#)-based humans, albeit vastly extended beyond the severe limitations of humans as we know them today, will live out on the web, projecting bodies whenever they need or want them, including virtual bodies in diverse realms of [virtual reality](#), holographically projected bodies, physical bodies comprised of [nanobot](#) swarms, and other forms of [nanotechnology](#).

A [software](#)-based [human](#) will be free, therefore, from the [constraints](#) of any particular [thinking](#) medium. Today, we are each confined to a mere hundred trillion connections, but humans at the end of the twenty-first century can grow their [thinking](#) and [thoughts](#) without limit. We may regard this as a form of [immortality](#), although it is worth pointing out that [data](#) and [information](#) do not necessarily last forever. Although not dependent on the viability of the [hardware](#) it runs on, the longevity of [information](#) depends on its

relevance, [utility](#), and [accessibility](#). If you've ever tried to retrieve [information](#) from an obsolete form of [data](#) storage in an old obscure format (e.g., a reel of magnetic tape from a 1970 [minicomputer](#)), you will understand the challenges in keeping [software](#) viable. However, if we are diligent in maintaining our [mind file](#), keeping current backups, and porting to current formats and mediums, then a form of [immortality](#) can be attained, at least for [software](#)-based humans. Our [mind file](#)--our personality, skills, memories--all of that is lost today when our [biological hardware](#) crashes. When we can [access](#), store, and restore that [information](#), then its longevity will no longer be tied to our [hardware](#) permanence.

Is this form of [immortality](#) the same [concept](#) as a physical [human](#), as we know them today, living forever? In one [sense](#) it is, because as I pointed out earlier, our contemporary selves are not a constant collection of [matter](#) either. Only our [pattern](#) of [matter](#) and [energy](#) persists, and even that gradually changes. Similarly, it will be the [pattern](#) of a [software human](#) that persists and develops and changes gradually.

But is that person based on my [mind file](#), who migrates across many [computational substrates](#), and who outlives any particular [thinking](#) medium, really me? We come back to the same questions of [consciousness](#) and [identity](#), issues that have been debated since the Platonic dialogues. As we go through the twenty-first century, these will not remain polite philosophical debates, but will be confronted as vital, practical, political, and legal issues.

A related question is "is [death](#) desirable?" A great deal of our effort goes into avoiding it. We make extraordinary efforts to delay it, and indeed often consider its intrusion a tragic [event](#). Yet we might find it hard to live without it. We consider [death](#) as giving meaning to our lives. It gives [importance](#) and value to [time](#). [Time](#) could become meaningless if there were too much of it.

The Next Step in [Evolution](#) and the Purpose of [Life](#)

But I regard the freeing of the [human mind](#) from its severe physical limitations of scope and duration as the necessary next step in [evolution](#). [Evolution](#), in my view, represents the purpose of [life](#). That is, the purpose of [life](#)--and of our lives--is to evolve. The [Singularity](#) then is not a grave danger to be avoided. In my view, this next [paradigm shift](#) represents the goal of our [civilization](#).

What does it mean to evolve? [Evolution](#) moves toward greater [complexity](#), greater elegance, greater [knowledge](#), greater [intelligence](#), greater [beauty](#), greater [creativity](#), and more of other abstract and subtle [attributes](#) such as [love](#). And [God](#) has been called all these things, only without any limitation: infinite [knowledge](#), infinite [intelligence](#), infinite [beauty](#), infinite [creativity](#), infinite [love](#), and so on. Of course, even the accelerating [growth](#) of [evolution](#) never achieves an infinite level, but as it explodes exponentially, it certainly moves rapidly in that direction. So [evolution](#) moves inexorably toward our [conception](#) of [God](#), albeit never quite reaching this ideal. Thus the freeing of our [thinking](#)

from the severe limitations of its [biological](#) form may be regarded as an essential [spiritual](#) quest.

In making this statement, it is [important](#) to emphasize that terms like [evolution](#), destiny, and [spiritual](#) quest are observations about the end result, not the basis for these predictions. I am not saying that [technology](#) will evolve to [human](#) levels and beyond simply because it is our destiny and because of the satisfaction of a [spiritual](#) quest. Rather my projections result from a [methodology](#) based on the [dynamics](#) underlying the (double) [exponential growth](#) of technological processes. The primary force driving [technology](#) is economic imperative. We are moving toward [machines](#) with [human](#) level [intelligence](#) (and beyond) as the result of millions of small advances, each with their own particular economic justification.

To use an example from my own [experience](#) at one of my companies (Kurzweil Applied [Intelligence](#)), whenever we came up with a slightly more intelligent version of speech recognition, the new version invariably had greater value than the earlier generation and, as a result, sales increased. It is interesting to note that in the example of speech recognition [software](#), the three primary surviving competitors stayed very close to each other in the [intelligence](#) of their [software](#). A few other companies that failed to do so (e.g., Speech [Systems](#)) went out of business. At any point in [time](#), we would be able to sell the version prior to the latest version for perhaps a quarter of the price of the current version. As for versions of our [technology](#) that were two generations old, we couldn't even give those away. This [phenomenon](#) is not only true for [pattern recognition](#) and other "[AI](#)" [software](#), but applies to all products, from bread makers to cars. And if the product itself doesn't exhibit some level of [intelligence](#), then [intelligence](#) in the manufacturing and marketing [methods](#) have a major effect on the success and profitability of an enterprise.

There is a vital economic imperative to create more intelligent [technology](#). Intelligent [machines](#) have enormous value. That is why they are being built. There are tens of thousands of projects that are advancing intelligent [machines](#) in diverse incremental ways. The support for "high tech" in the business community (mostly [software](#)) has grown enormously. When I started my [optical character recognition \(OCR\)](#) and speech [synthesis](#) company (Kurzweil [Computer](#) Products, Inc.) in 1974, there were only a half-dozen high [technology](#) IPO's that year. The [number](#) of such deals has increased one hundred fold and the [number](#) of dollars invested has increased by more than one thousand fold in the past 25 years. In the four years between 1995 and 1999 alone, high tech [venture capital](#) deals increased from just over \$1 billion to approximately \$15 billion.

We will continue to build more powerful [computational](#) mechanisms because it creates enormous value. We will reverse-[engineer](#) the [human brain](#) not simply because it is our destiny, but because there is valuable [information](#) to be found there that will provide insights in building more intelligent (and more valuable) [machines](#). We would have to repeal [capitalism](#) and every visage of economic competition to stop this [progression](#).

By the second half of this next century, there will be no clear distinction between [human](#) and [machine intelligence](#). On the one hand, we will have [biological](#) brains vastly expanded through distributed [nanobot](#)-based implants. On the other hand, we will have fully [nonbiological](#) brains that are copies of [human](#) brains, albeit also vastly extended. And we will have a myriad of other varieties of intimate connection between [human thinking](#) and the [technology](#) it has fostered.

Ultimately, [nonbiological intelligence](#) will dominate because it is growing at a double exponential rate, whereas for all practical purposes [biological intelligence](#) is at a standstill. [Human thinking](#) is stuck at 10^{26} calculations per second (for all [biological](#) humans), and that figure will never appreciably change (except for a small increase resulting from genetic [engineering](#)). [Nonbiological thinking](#) is still millions of times less today, but the cross over will occur before 2030. By the end of the twenty-first century, [nonbiological thinking](#) will be trillions of trillions of times more powerful than that of its [biological](#) progenitors, although still of [human](#) origin. It will continue to be the [human-machine civilization](#) taking the next step in [evolution](#).

Most forecasts of the [future](#) seem to ignore the revolutionary impact of the [Singularity](#) in our [human](#) destiny: the inevitable emergence of [computers](#) that match and ultimately vastly exceed the capabilities of the [human brain](#), a development that will be no less [important](#) than the [evolution](#) of [human intelligence](#) itself some thousands of centuries ago. And the primary [reason](#) for this failure is that they are based on the intuitive but short sighted [linear](#) view of [history](#).

Before the next century is over, the [Earth's technology-creating species](#) will [merge](#) with its [computational technology](#). There will not be a clear distinction between [human](#) and [machine](#). After all, what is the difference between a [human brain](#) enhanced a trillion fold by [nanobot](#)-based implants, and a [computer](#) whose design is based on high resolution scans of the [human brain](#), and then extended a trillion-fold?

Why [SETI](#) Will Fail (and why we are alone in the [Universe](#))

The [law of accelerating returns](#) implies that by 2099, the [intelligence](#) that will have emerged from [human-machine civilization](#) will be trillions of trillions of times more powerful than it is today, dominated of course by its [nonbiological](#) form.

So what does this have to do with [SETI](#) (the [Search](#) for Extra Terrestrial [Intelligence](#))? The naïve view, going back to pre-Copernican days, was that the [Earth](#) was at the center of the [Universe](#), and [human intelligence](#) its greatest gift (next to [God](#)). The more informed recent view is that even if the likelihood of a [star](#) having a [planet](#) with a [technology](#) creating [species](#) is very low (e.g., one in a million), there are so many stars (i.e., billions of trillions of them), that there are bound to be many with advanced [technology](#).

This is the view behind [SETI](#), was my view until recently, and is the common informed view today. Although [SETI](#) has not yet looked everywhere, it has already covered a substantial portion of the [Universe](#).

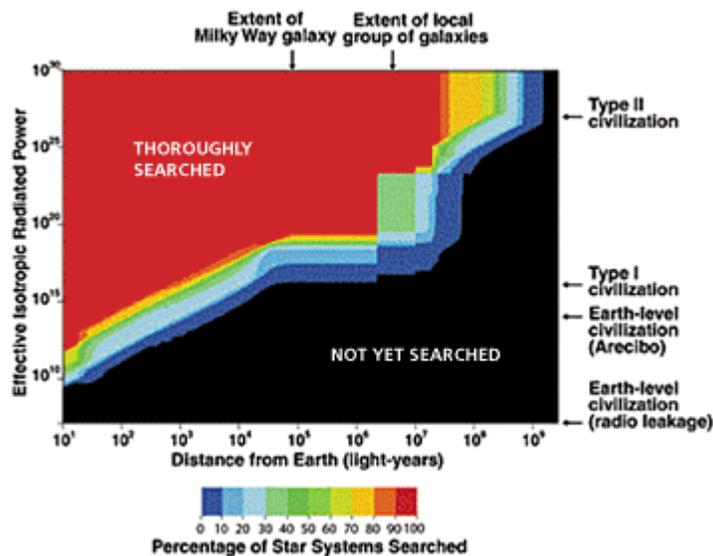


Chart by Scientific American

In the above diagram (courtesy of Scientific American), we can see that [SETI](#) has already thoroughly [searched](#) all [star systems](#) within 10^7 [light-years](#) from [Earth](#) for alien [civilizations](#) capable (and willing) to transmit at a power of at least 10^{25} watts, a so-called Type II [civilization](#) (and all [star systems](#) within 10^6 [light-years](#) for transmission of at least 10^{18} watts, and so on). No sign of [intelligence](#) has been found as of yet.

In a recent [email](#) to my [research](#) assistant, Dr. Seth Shostak of the [SETI](#) Institute points out that a new comprehensive targeted [search](#), called Project Phoenix, which has up to 100 times the sensitivity and covers a greater range of the radio dial as compared to previous [searches](#), has only been applied thus far to 500 [star systems](#), which is, of course only a minute fraction of the half trillion [star systems](#) in just our own [galaxy](#).

However, according to my model, once a [civilization](#) achieves our own level ("Earth-level") of radio transmission, it takes no more than one century, two at the most, to achieve what [SETI](#) calls a Type II [civilization](#). If the assumption that there are at least millions of radio capable [civilizations](#) out there, and that these [civilizations](#) are spread out over millions (indeed billions) of years of development, then surely there ought to be millions that have achieved Type II status.

Incidentally, this is not an argument against the [SETI](#) project, which in my view should have the highest possible priority because the negative finding is no less significant than a positive result.

It is odd that we find the cosmos so silent. Where is everybody? There should be millions of [civilizations](#) vastly more advanced than our own, so we should be noticing their

[broadcasts](#). A sufficiently advanced [civilization](#) would not be likely to restrict its [broadcasts](#) to subtle signals on obscure frequencies. Why are they so silent, and so shy?

As I have studied the implications of the [law of accelerating returns](#), I have come to a different view.

Because [exponential growth](#) is so explosive, it is the case that once a [species](#) develops computing [technology](#), it is only a [matter](#) of a couple of centuries before the [nonbiological](#) form of their [intelligence](#) explodes. It permeates virtually all [matter](#) in their vicinity, and then inevitably expands outward close to the maximum speed that [information](#) can travel. Once the [nonbiological intelligence](#) emerging from that [species'](#) [technology](#) has saturated its vicinity (and the [nature](#) of this saturation is another complex issue, which I won't deal with in this essay), it has no other way to continue to evolve but to expand outwardly. The expansion does not start out at the maximum speed, but quickly achieves a speed within a vanishingly small delta from the maximum speed.

What is the maximum speed? We currently understand this to be the speed of [light](#), but there are already tantalizing hints that this may not be an absolute limit. There were recent [experiments](#) that measured the flight [time](#) of [photons](#) at nearly twice the speed of [light](#), a result of quantum uncertainty on their position. However, this result is actually not useful for this analysis, because it does not actually allow [information](#) to be communicated at faster than the speed of [light](#), and we are fundamentally interested in [communication](#) speed.

Quantum disentanglement has been measured at many times the speed of [light](#), but this is only communicating randomness (profound quantum randomness) at speeds far greater than the speed of light; again, this is not [communication](#) of [information](#) (but is of great interest for restoring [encryption](#), after [quantum computing](#) destroys it). There is the potential for worm holes (or folds of the [Universe](#) in dimensions beyond the three visible ones), but this is not really traveling at faster than the speed of [light](#), it just means that the topology of the [Universe](#) is not the simple three dimensional [space](#) that naïve [physics](#) implies. But we already knew that. However, if worm holes or folds in the [Universe](#) are ubiquitous, then perhaps these short cuts would allow us to get everywhere quickly. Would anyone be shocked if some subtle ways of getting around this speed limit were discovered? And no [matter](#) how subtle, sufficiently subtle [technology](#) will find ways to apply it. The point is that if there are ways around this limit (or any other currently understood limit), then the extraordinary levels of [intelligence](#) that our [human-machine civilization](#) will achieve will find those ways and exploit them.

So for now, we can say that ultra high levels of [intelligence](#) will expand outward at the speed of [light](#), but recognize that this may not be the actual limit of the speed of expansion, or even if the limit is the speed of [light](#) that this limit may not restrict reaching other locations quickly.

Consider that the [time](#) spans for [biological evolution](#) are measured in millions and billions of years, so if there are other [civilizations](#) out there, they would be spread out by

huge spans of [time](#). If there are a lot of them, as contemporary [thinking](#) implies, then it would be very unlikely that at least some of them would not be ahead of us. That at least is the [SETI](#) assumption. And if they are ahead of us, they likely would be ahead of us by huge spans of [time](#). The likelihood that any [civilization](#) that is ahead of us is ahead of us by only a few decades is extremely small.

If the [SETI](#) assumption that there are many (e.g., millions) of technological (at least radio capable) [civilizations](#) is correct, then at least some of them (i.e., millions of them) would be way ahead of us. But it takes only a few centuries at most from the advent of [computation](#) for that [civilization](#) to expand outward at at least [light](#) speed. Given this, how can it be that we have not noticed them?

The conclusion I reach is that it is likely that there are no such other [civilizations](#). In other words, we are in the lead. That's right, our humble [civilization](#) with its Dodge pick up trucks, fried chicken fast food, and ethnic cleansings (and [computation](#)!) is in the lead.

Now how can that be? Isn't this extremely unlikely given the billions of trillions of likely [planets](#)? Indeed it is very unlikely. But equally unlikely is the [existence](#) of our [Universe](#) with a [set](#) of laws of [physics](#) so exquisitely precisely what is needed for the [evolution](#) of [life](#) to be possible. But by the Anthropic principle, if the [Universe](#) didn't allow the [evolution](#) of [life](#) we wouldn't be here to notice it. Yet here we are. So by the same Anthropic principle, we're here in the lead in the [Universe](#). Again, if we weren't here, we would not be noticing it.

Let's consider some arguments against this perspective.

Perhaps there are extremely advanced technological [civilizations](#) out there, but we are outside their [light](#) sphere of [intelligence](#). That is, they haven't gotten here yet. Okay, in this case, [SETI](#) will still fail because we won't be able to see (or hear) them, at least not before we reach [Singularity](#).

Perhaps they are amongst us, but have decided to remain invisible to us. Incidentally, I have always considered the [science fiction](#) notion of large [space](#) ships with large squishy creatures similar to us to be very unlikely. Any [civilization](#) sophisticated enough to make the trip here would have long since passed the point of merging with their [technology](#) and would not need to send such physically bulky [organisms](#) and equipment. Such a [civilization](#) would not have any unmet material needs that require it to steal physical resources from us. They would be here for observation only, to gather [knowledge](#), which is the only resource of value to such a [civilization](#). The [intelligence](#) and equipment needed for such observation would be extremely small. In this case, [SETI](#) will still fail because if this [civilization](#) decided that it did not want us to notice it, then it would succeed in that desire. Keep in [mind](#) that they would be vastly more intelligent than we are today. Perhaps they will reveal themselves to us when we achieve the next level of our [evolution](#), specifically merging our [biological](#) brains with our [technology](#), which is to say, after the [Singularity](#). Moreover, given that the [SETI](#) assumption implies that there

are millions of such highly developed [civilizations](#), it seems odd that all of them have made the same decision to stay out of our way.

Why [Intelligence](#) is More Powerful than [Physics](#)

As [intelligence](#) saturates the [matter](#) and [energy](#) available to it, it turns dumb [matter](#) into smart [matter](#). Although smart [matter](#) still nominally follows the laws of [physics](#), it is so exquisitely intelligent that it can harness the most subtle aspects of the laws to manipulate [matter](#) and [energy](#) to its will. So it would at least appear that [intelligence](#) is more powerful than [physics](#).

Perhaps what I should say is that [intelligence](#) is more powerful than [cosmology](#). That is, once [matter](#) evolves into smart [matter](#) ([matter](#) fully saturated with [intelligence](#)), it can manipulate [matter](#) and [energy](#) to do whatever it wants. This perspective has not been considered in discussions of [future cosmology](#). It is assumed that [intelligence](#) is irrelevant to events and processes on a cosmological scale. Stars are born and die; galaxies go through their cycles of creation and destruction. The [Universe](#) itself was born in a big bang and will end with a crunch or a whimper, we're not yet sure which. But [intelligence](#) has little to do with it. [Intelligence](#) is just a [bit](#) of froth, an ebullition of little creatures darting in and out of inexorable universal forces. The mindless mechanism of the [Universe](#) is winding up or down to a distant [future](#), and there's nothing [intelligence](#) can do about it.

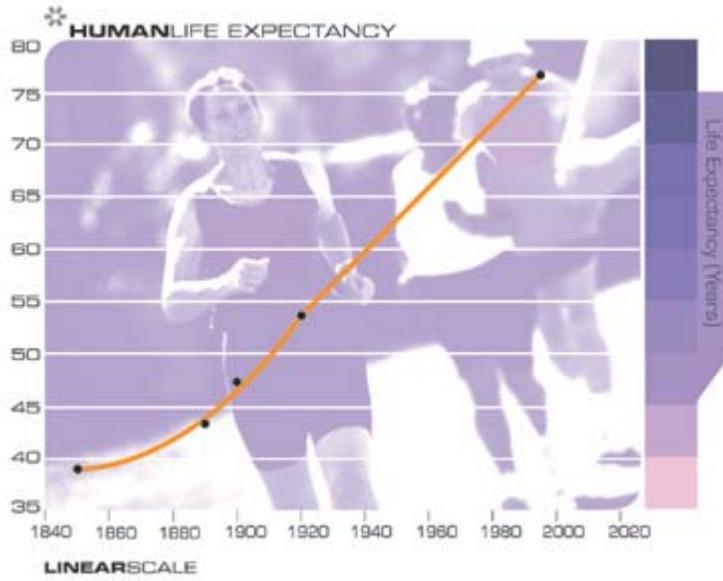
That's the common [wisdom](#), but I don't agree with it. [Intelligence](#) will be more powerful than these impersonal forces. Once a [planet](#) yields a [technology](#) creating [species](#) and that [species](#) creates [computation](#) (as has happened here on [Earth](#)), it is only a [matter](#) of a few centuries before its [intelligence](#) saturates the [matter](#) and [energy](#) in its vicinity, and it begins to expand outward at the speed of [light](#) or greater. It will then overcome [gravity](#) (through exquisite and vast [technology](#)) and other cosmological forces (or, to be fully accurate, will maneuver and control these forces) and create the [Universe](#) it wants. This is the goal of the [Singularity](#).

What kind of [Universe](#) will that be? Well, just wait and see.

Plan to Stick Around

Most of you (again I'm using the plural form of the word) are likely to be around to see the [Singularity](#). The expanding [human life](#) span is another one of those [exponential trends](#). In the eighteenth century, we added a few days every year to [human](#) longevity; during the nineteenth century we added a couple of weeks each year; and now we're adding almost a half a year every year. With the revolutions in [genomics](#), proteomics, rational drug design, therapeutic cloning of our own organs and tissues, and related developments in bio-[information sciences](#), we will be adding more than a year every year within ten years. So take care of yourself the old fashioned way for just a little while longer, and you may actually get to [experience](#) the next fundamental [paradigm shift](#) in

our destiny.



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