Dancing with the Red Queen: Linear Intelligence in an Exponential World

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by

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Disclamer:

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ABSTRACT

The world is experiencing exponential growth along many dimensions. Human beings, while generally comfortable with linear thinking, have a difficult time appreciating the impact of exponential thinking. As a result, those large organizations that plan for linear growth fall behind faster and faster every year. Those organizations that can ride the exponential growth curves ensure for themselves huge advantages with respect to their competitors, as well as help themselves survive into the future.

The Intelligence Community must incorporate the effects of the following four exponential trends, or suffer the dangerous consequences of not being able to fulfill our mission to protect the nation's security.

- Accessing the internet wirelessly
- Miniaturization of devices
- Decline in the cost of computing
- Rise of social software

Combined, these four growth trends will create a world for which the IC is grossly unprepared. Preparation for this new world must start now.

INTRODUCTION

The sequel to the famous children's story, Alice's Adventures in Wonderland (Carroll 1865), is Through the Looking Glass (Carroll 1872). In the sequel, the main character, Alice, finds herself

playing a life size chess game. The board squares are a variety of wooded, grassy, and cultivated fields in the countryside. Alice is playing the part of one of the White Queen's pawns. Her opponent is the somewhat insane animated playing card, known as the Red Queen of Hearts. The queen has promised Alice a throne, if she (Alice) can move herself to the eighth rank (eighth row). The book chronicles Alice's adventures as she progresses across the fields toward the eighth rank.

In Chapter 2, "The Garden of Live Flowers," Alice tries to climb a hill to get a better view of the landscape. In spite of her attempts to ascend the hill, she makes little progress. The Red Queen comes along and takes Alice's hand. The queen begins running, pulling Alice along. They continue running at top speed for some time. All the while, the Red Queen shouts, "Faster! Faster!" Alice eventually collapses under a tree.

> Alice looked round her in great surprise. "Why, I do believe we've been under this tree the whole time! Everything's just as it was!"
>
> "Of course it is," said the Queen, "what would you have it?"
>
> "Well, in OUR country," said Alice, still panting a little, "you'd generally get to somewhere else--if you ran very fast for a long time, as we've been doing."
>
> "A slow sort of country!" said the Queen. "Now, HERE, you see, it takes all the running YOU can do, to keep in the same place. If you want to get somewhere else, you must run at least twice as fast as that!"

The Red Queen implicitly understood the 21st Century--we have to run faster each year just to keep up with the changes. Running faster and faster each year is an exponential way of thinking. On the other hand, to think that by taking three steps we should make three steps of progress is linear thinking. Alice was thinking linearly, while the Red Queen was thinking exponentially. If we want to get ahead of the changes now occurring in the world, we have to run twice as fast as what we would normally think.

AN EXPONENTIAL EXAMPLE

The ancient Hindu legend of Ambalappuzha Paal Payasam (Wikipedia 2007a) is retold for a modern audience by Birch and Grebu (1988) as a story about the King of Deccan. In the story, the king wanted to reward one of his wise servants for his service. The servant at first declined any reward, but the king insisted. The king demanded that the servant name his reward. The servant, pondering the king's chessboard, eventually suggested a modest reward of a few grains of rice.

> I ask only this: Tomorrow, for the first square of your chessboard, give me one grain of rice; the next day, for the second square, two grains of rice; the next day after that, four grains of rice; then the following day, eight grains of rice for the next square of your chessboard. Thus for each square give me twice the number of grains of the square before it, and so on for every square of the chessboard.

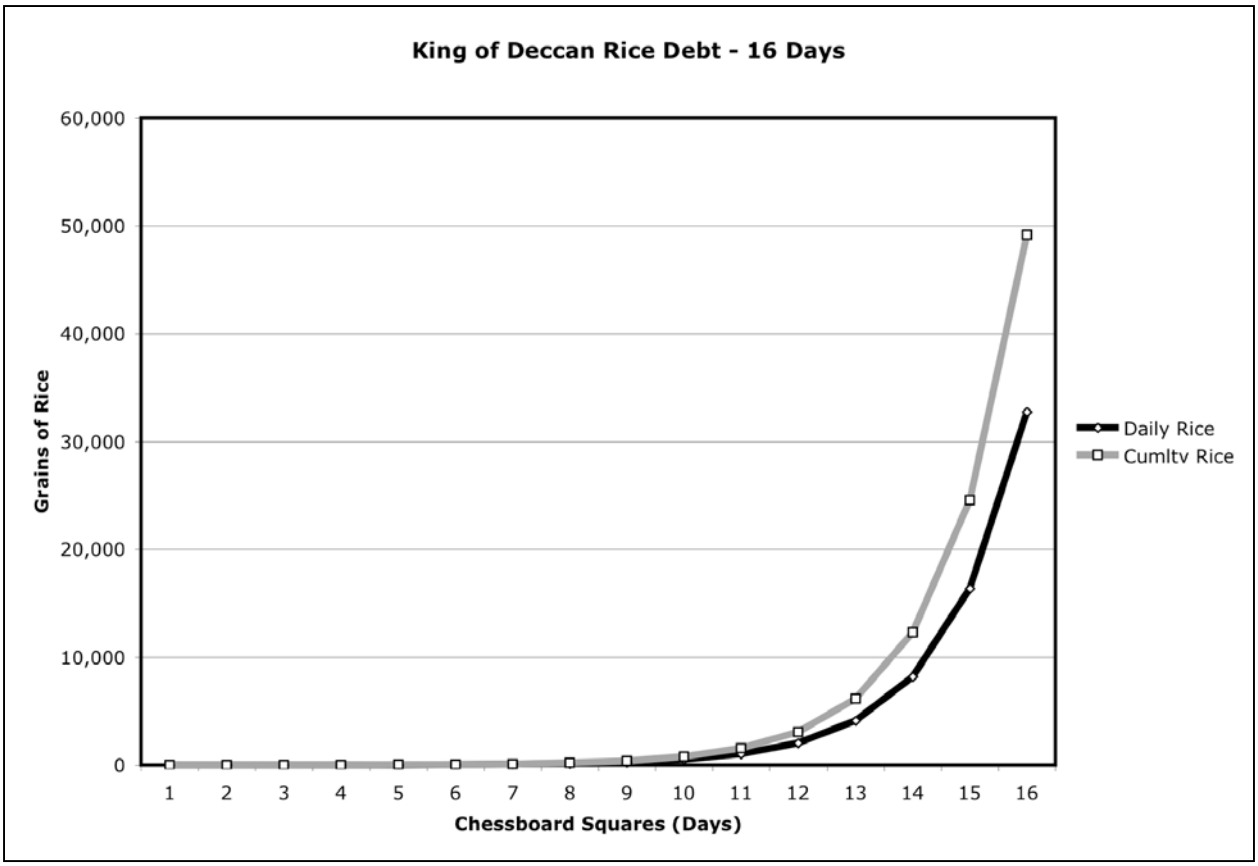
The king, being a good linear thinker, agreed--thinking that he would get away with delivering just a handful of rice to pay the reward. After a few days of delivering the daily reward, the king

promptly forgot about the reward and went on vacation. After the king's return, he started to notice that cartloads of rice were being delivered to the wise man. The king demanded to know what was going on. The director of the granary suggested the king consult with his mathematicians. The mathematicians told the king that this promise would bankrupt him long before the debt was paid.

The king summoned the wise servant and asked what it would take to be released from his promise. The wise man reminded the king that it was the king who had insisted on giving a reward. The wise man said he would be satisfied when the king was satisfied that the reward was enough. This circumstance forced the king to admit his foolishness and cancel the reward. From then on, the king improved his administration by no longer making impulsive decisions based on ignorance and pride.

EXPONENTIAL CURVES

The following two charts show the exponential growth in the daily amount of rice owed by the King of Deccan over a 16-day period and over the entire 64-day period. The cumulative amount owed is also shown. The number of grains owed on day 8 was 128, by day 16 it was 32,800, by day 32 it was 2,150,000,000 (2 billion), and on day 64 it was 9,220,000,000,000,000,000 (9 Quintillion).



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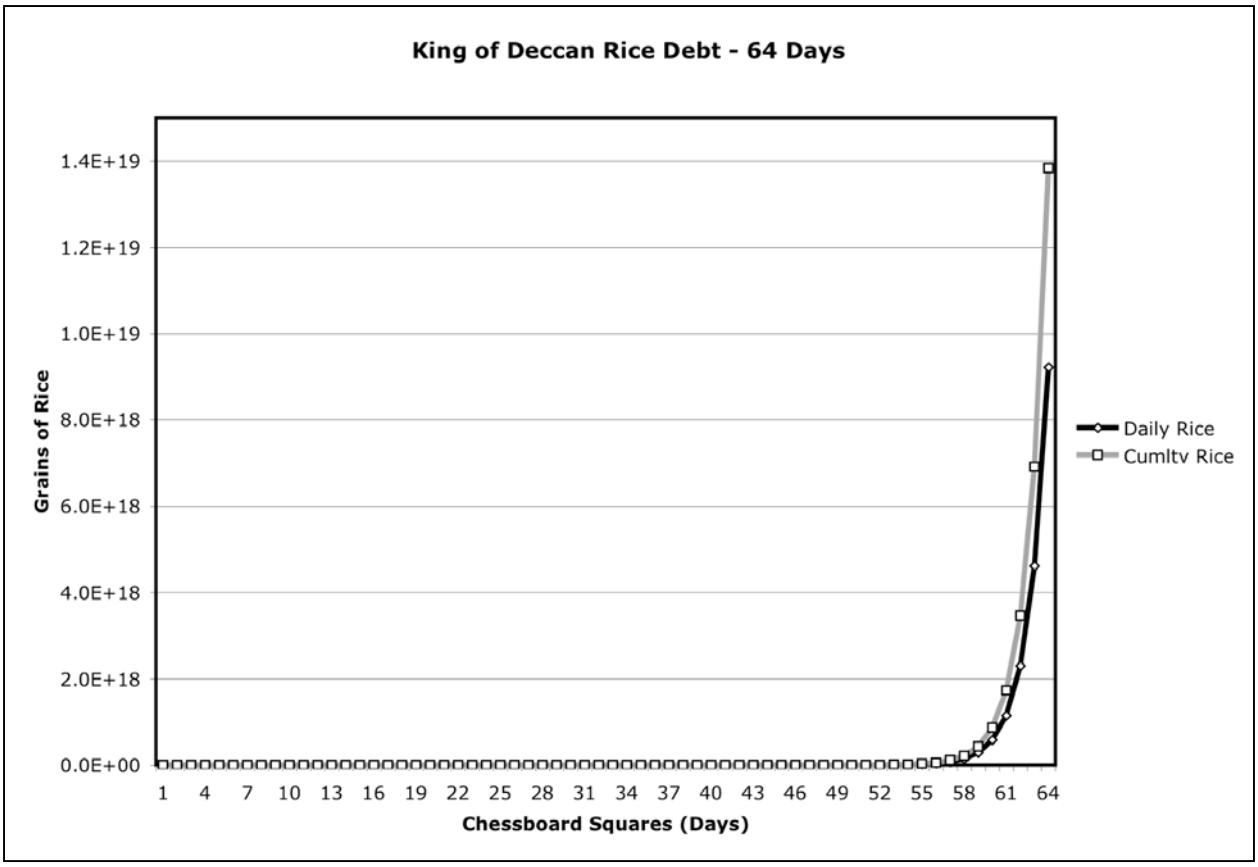

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To get some perspective, a grain of rice weighs about 0.0275 grams (Songfa 1995). This means on day 8 the king owed about 3.5 grams; on day 16 about 900 grams (or just less than one kilo); on day 32, the king owed about 59 metric tonnes (a metric tonne is 1,000 kilos); and on day 64 the king owed about 254,000,000,000 metric tonnes (254 gigatonnes). By comparison, in 2004 the global production of rice was 610 megatonnes (IRRI 2007). At today's production rate, it would take the entire earth's rice farmers 416 years to produce the amount of rice the king owed the wise man on just the last day.

A MODERN EXAMPLE

It took researchers about 10 years (1965-1975) to map the first human gene (Kurzweil 2001). Over the next 15 years (1975-1990) they mapped another 10 genes. So when the Human Genome Project (Human Genome Program 2007) (HGP) began in 1990 with the goal of mapping all 25,000 human genes in 15 years, critics were extremely skeptical. Over the previous 25 years, researchers had averaged about 1 gene every 14 months. Even at an optimistic 1 gene a year, it would take 20,000 years or more. The critics, of course, were engaged in linear thinking at its best. These critics felt vindicated when five years later, the HGP had only mapped about 100 genes. Even two-thirds of the way into the program (10 years) they had only mapped 10 percent of the genes. Then the effects of exponential growth became manifest. Over the next three years, the HPG completed the other 90 percent of their tasks--finishing two years early and under budget.

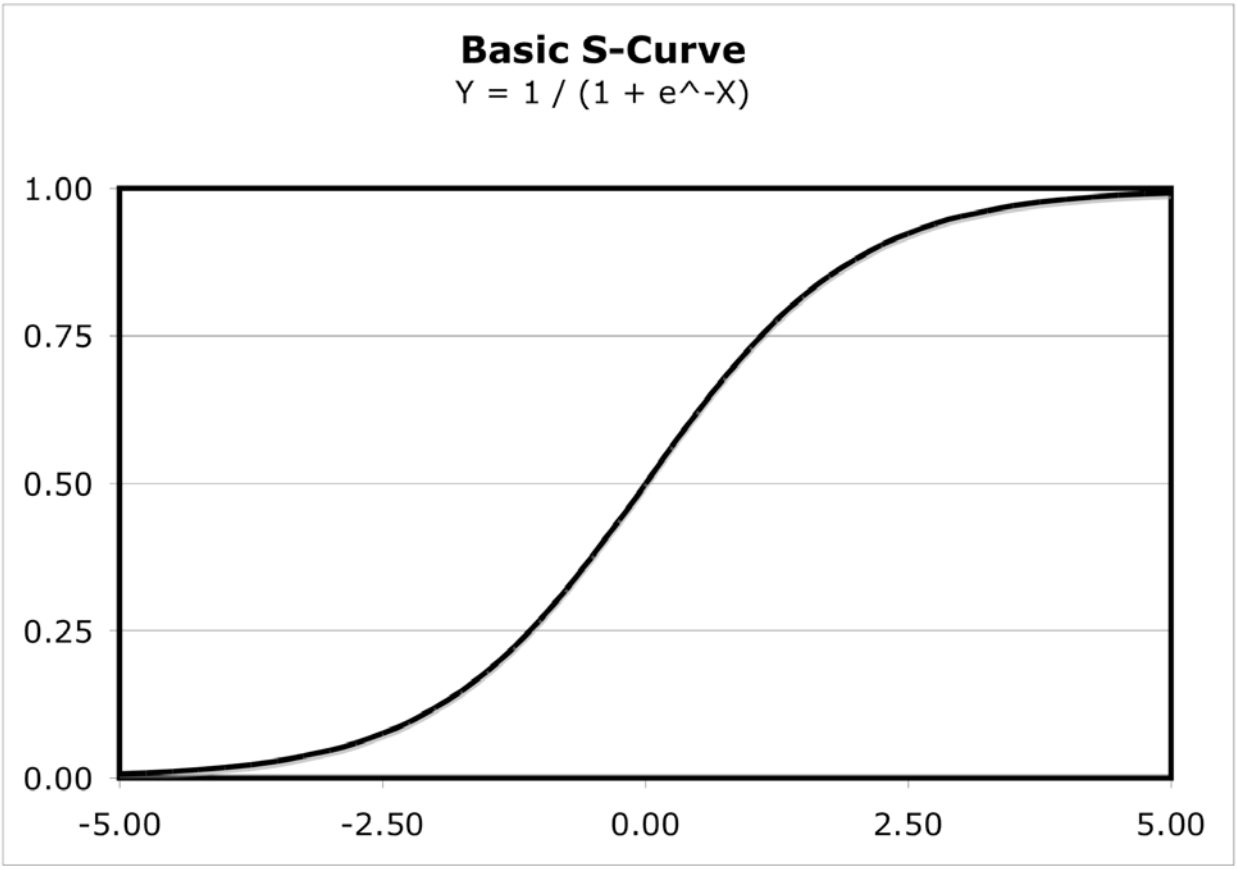
Wow! For the linear thinking critics, this dramatic finish came out of nowhere. Thinking the way they did, they could not comprehend how the task could have ever been completed and had felt justified in calling for the program's termination.

- So what explains the exponential growth? Over the course of the years, many more people learned how to do gene mapping, thus many more people were working on the problem. More importantly, however, the knowledge about how to map genes was compounding and being embedded in sequencing machines. During the course of the project, the cost of sequencing DNA base pairs dropped from about $10 a pair to about 1 cent a pair. That is a three orders of magnitude drop in cost. Therefore, when many

more researchers are working on the project and each being a thousand times more productive than at the beginning, the completion rate "takes off."

LIMITING FACTORS

Exponential growth rates cannot continue forever. At some point, there are factors that limit growth. For example, the earth does not have enough rice farmers to grow the amount of rice the king owed his servant. At some point, the king would have to default on his promise. When limiting factors are applied gracefully, growth rates decline reasonably and the result is an S-curve graph (Wikipedia 2007b). In the two charts below, we first display the Basic S-Curve and then we display the diffusion of television sets throughout US homes from 1945 to 1965. Notice how closely the actual data mirrors the theoretical curve. The diffusion of other innovations--especially technologies like the telephone, radio sets, VCRs, PCs, cell phones, etc.--follow this same S-Curve pattern, though over very different time scales. The house telephone took more than 70 years to reach saturation. The television took about 20 years; and the VCR only took about 10 years (Census Bureau 2007). Our personal observations indicate that the adoption of MySpace (www.myspace.com) by most US teenagers took about three years.



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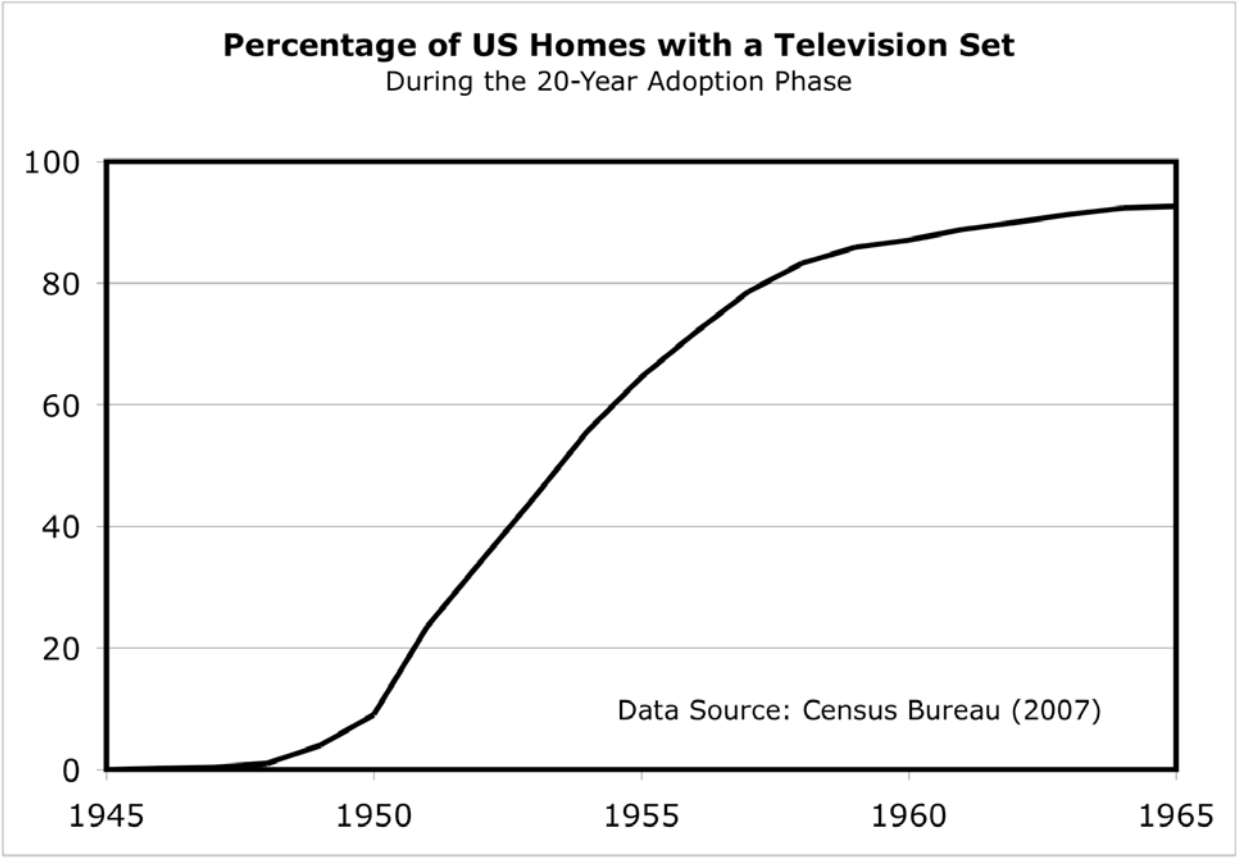

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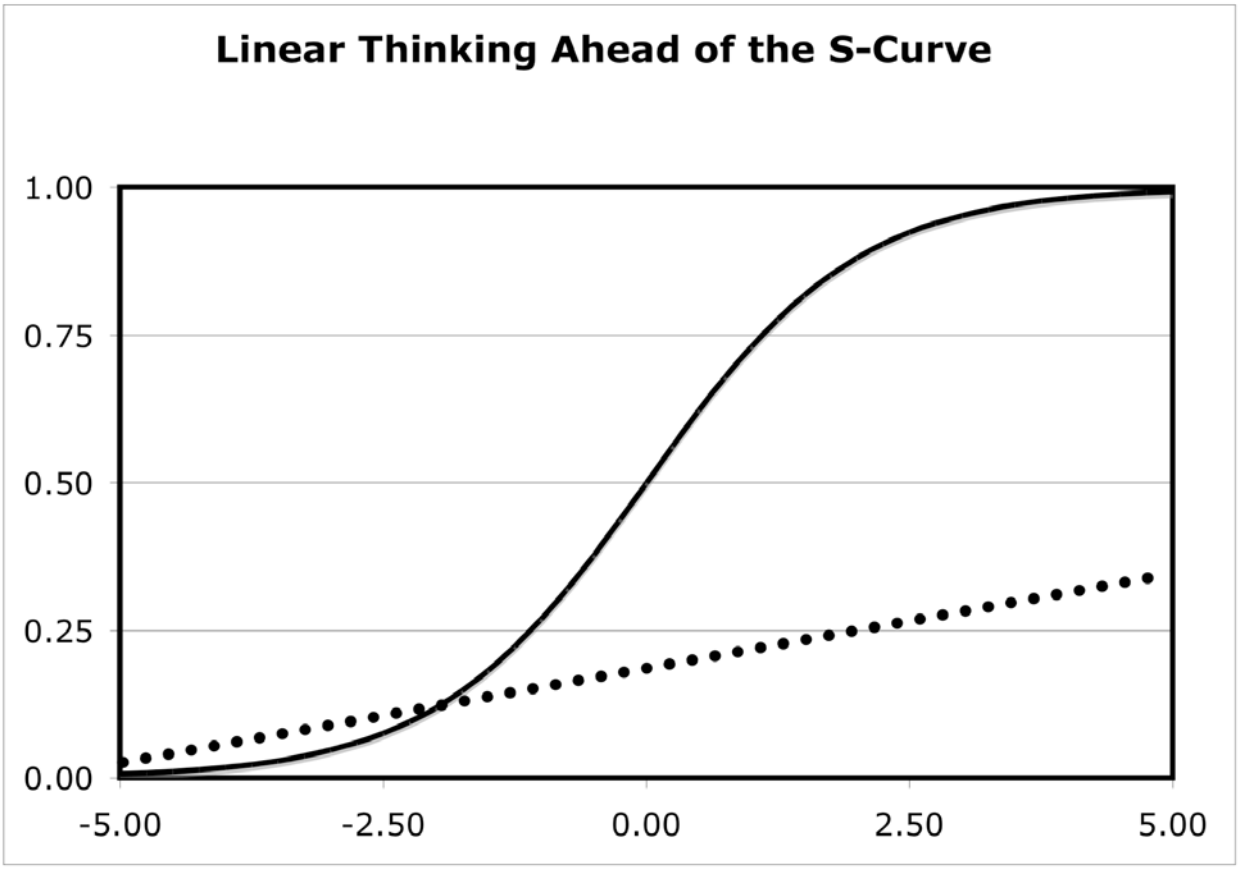
PITFALLS OF LINEAR THINKING

Linear thinking in an era of exponential change is dangerous. Linear thinking causes us to be blind-sided by trends that appear to come out of nowhere. Linear thinking also causes us to under-invest in areas that give our enemies a competitive advantage over us.

Consider the following two charts. In the first, the perceptive manager sees a trend developing and begins to expend resources ahead of the curve. However, in the age of exponential growth the modest "ahead of the curve" investments get blown away by the actual growth in the trend. After the trend has taken off, there is seemingly no way to catch up. In the second case, a less

prescient manager finally notices that his organization is behind the curve and begins an accelerated investment. Again, the linear investment is too little, too late--and there is seemingly no way to catch up. The gap between the exponential and linear curves is the vulnerability gap. In either case, the only way to patch the vulnerability is through some kind of discontinuous (disruptive) change.



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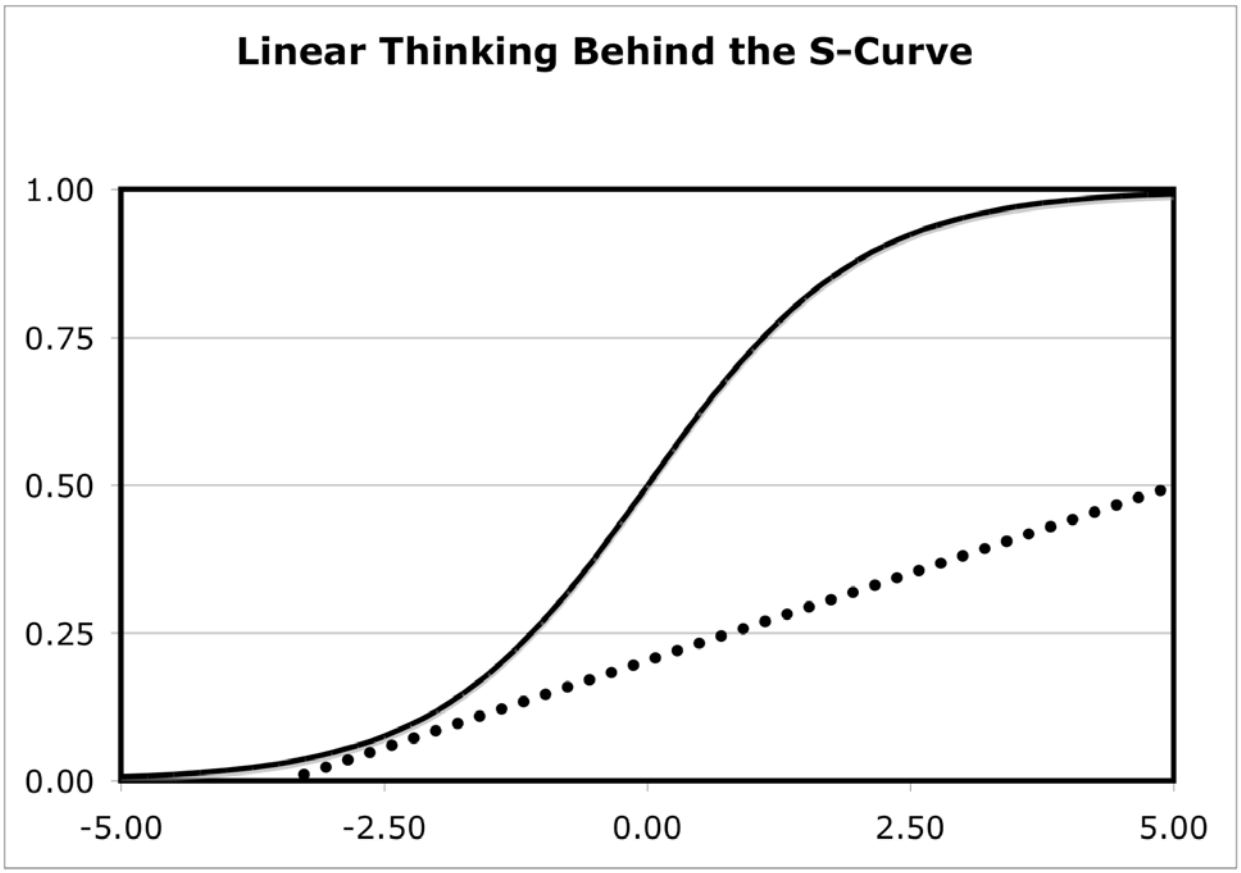

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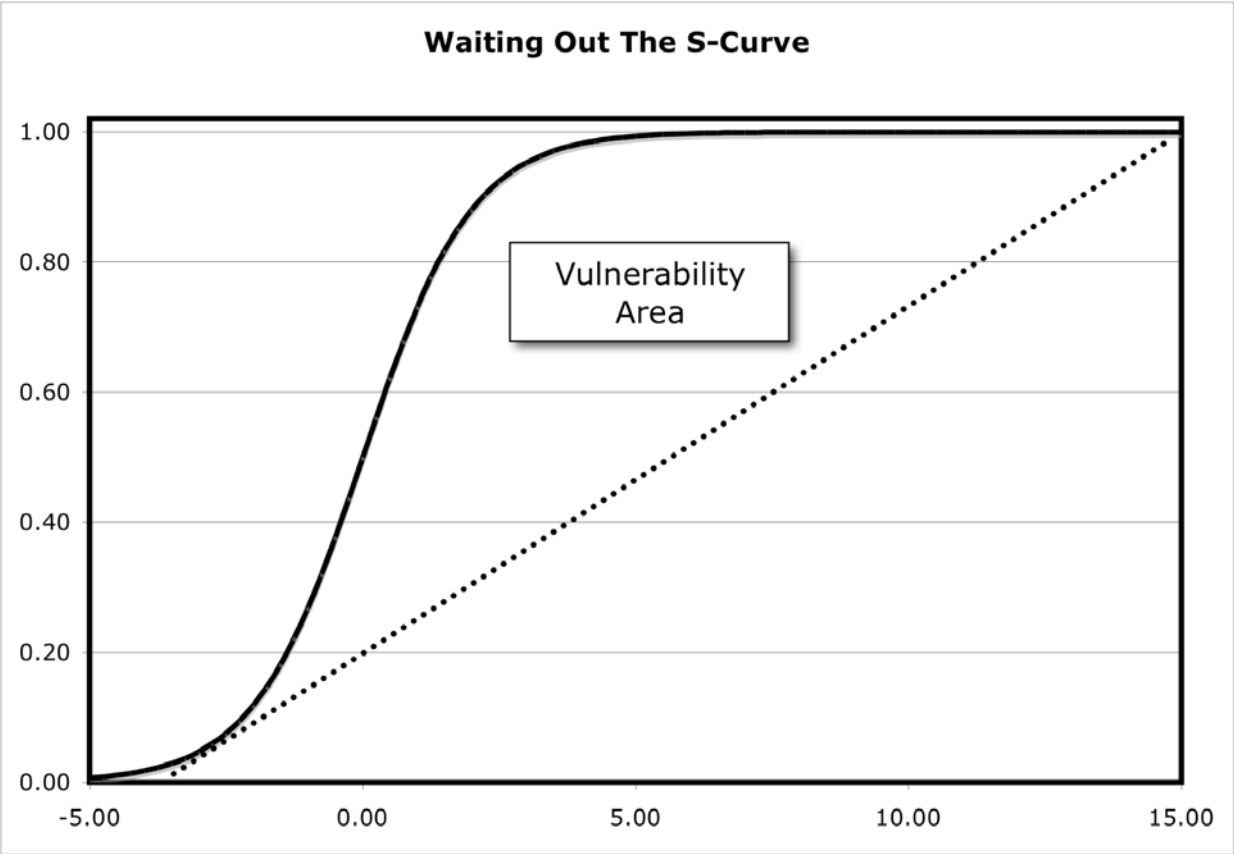
One might say, "well, the exponential trend can't continue forever, so eventually my linear investment will catch up." True enough. See the next chart. Using a linear strategy to outlast an S-Curve, however, leaves a gap--also known as a vulnerability.



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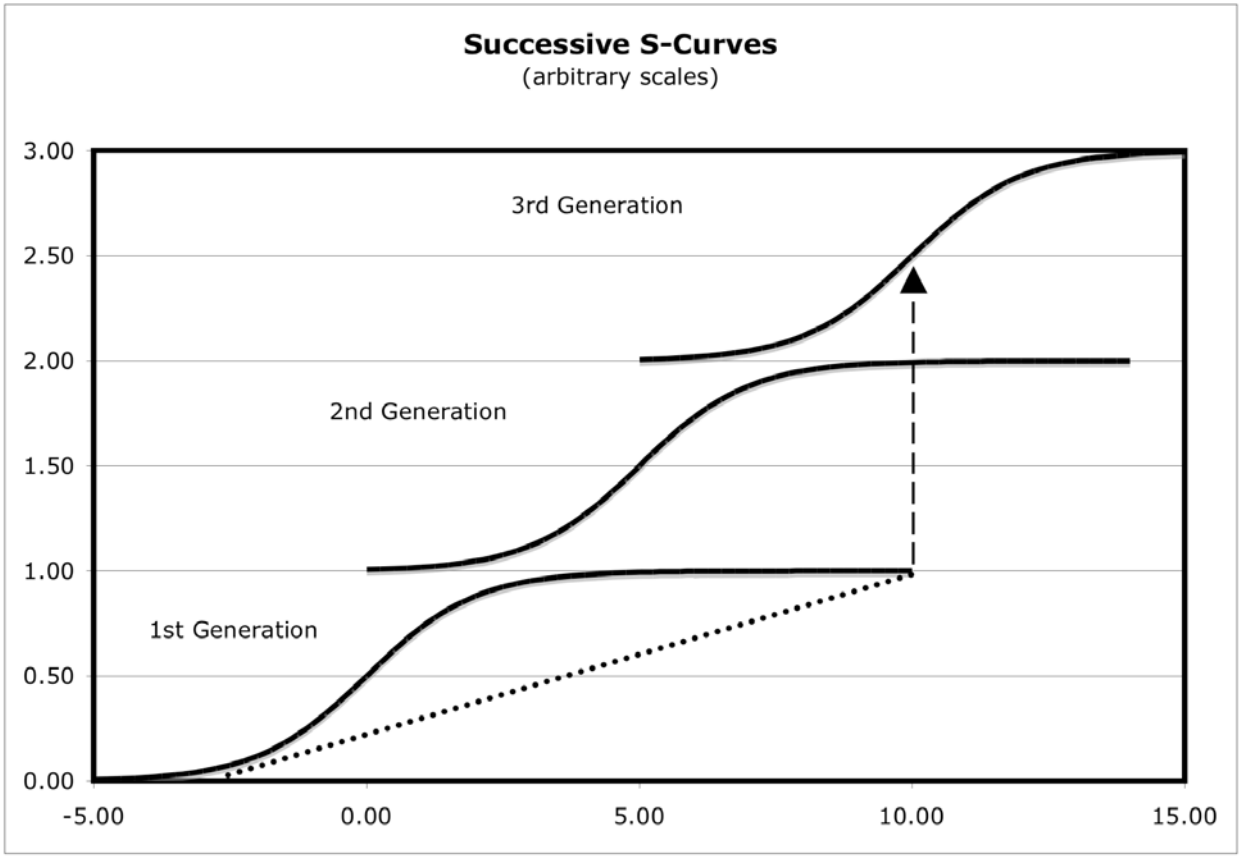
Creating a vulnerability is the first reason using a linear strategy is a risky bet. The second reason is that one generally does not know how far the trend will go up before it levels off. Consider the case of exponential miniaturization. Miniaturization allows us to put more and more components into the same space, or the same number of components in a smaller space.

- Nobel laureate, Richard Feynman, in his famous 1959 essay, "Plenty of Room at the Bottom" (Feynman 1959) reminds us that we are many (human and technological) generations away from reaching the (atomic) limits of miniaturization. In essence, hoping a linear approach will eventually catch up to the limiting (atomic) factor of

exponential growth in miniaturization is a false hope in the 21st century. The IC will have to deal aggressively with it now.

Thirdly, a linear approach assumes there is no follow-on exponential trend. In the following chart, we show that the linear investment does indeed catch up with an exponential trend that has leveled off. But it also shows that by the time the linear and S-curves meet, the linear investment is a generation and a half behind the subsequent S-curve trends.



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For example, assume the first generation in the graph is word processing, the second generation is email, and the third generation is instant messaging. These three capabilities are strategic enablers for any large organization, especially knowledge-intensive organizations like intelligence agencies. If an agency adopts a linear long-term deployment of word processing to all its employees, by the time they finish they will be severely disadvantaged, having missed the email and instant messaging revolutions. These generations of successive exponential growth do not stop. An organization must keep up, or give up.

DYING ON THE LINEAR VINE

Two of the major economic powerhouses of the 20th century were Bethlehem Steel (Wikipedia 2007c) and International Business Machines (Wikipedia 2007d). Both were founded in the late 19th century. They employed thousands and created wealth for millions of stockholders. Both contributed to the US victory in World War II. They both represented the best that American industry had to offer. Yet one company exists today and the other one doesn't. What was the difference?

- There are a number of explanations offered to explain the demise of Bethlehem Steel. The two most popular are that the steel company did not come to grips with 1) the rise of foreign steel competition, and 2) the rise of domestic "designer" steel companies. In either case, Bethlehem Steel stuck to its core business, making better and better quality steel, until the day it died. It ignored the exponential rise in the capability of its competitors, pursuing instead a linear quality improvement program. Game over! IBM, on the other hand, no longer makes typewriters. They no longer make punch card

machines. They rose the PC exponential curve and then got off at the top--they are no longer in the PC business. They are the largest IT company in the world. That is no small feat considering the “Dot Com” bust and competitors like Microsoft and Google.

Not only do companies in the commercial sector die when they act linearly in an exponential world, so too, can government agencies die following the same practice.

Let us consider the following three successive S-curve adoption curves: dial-up Internet access, hi-speed (DSL/cable) Internet access, and wireless hi-speed Internet access. The United States consumer and commercial sectors are in the beginning of the third (wireless) phase. Cities are beginning to deploy city-wide wireless hi-speed access (Wireless Philadelphia 2007). Indeed, Singapore intends to give free hi-speed wireless access to their whole country within the next three years (Infocom Development Authority 2007).

- Now consider this: there is one major intelligence agency which only gives dial-up access to the Internet to (not quite all) of its employees. Other major intelligence agencies give regular hi-speed access to the Internet to their employees, but are pretending that wireless hi-speed will go away if they ignore it long enough. As a community, we are anywhere from one to two technology generations behind.

An acquaintance recently remarked, "Give me a wireless internet-connected laptop and let me take that SAT exam again. I'll ace it." There is no question that a human being with a hi-speed wireless connection to the internet is orders of magnitude smarter than a human without one.

Refusing to give hi-speed internet access to our intelligence officers comparatively “dumbs down” the workforce by orders of magnitude. For an intelligence agency whose mission it is to outsmart our enemies, the lack of hi-speed access to the Internet for its employees is unforgivable. For the other agencies to ignore wireless hi-speed becomes equally unforgivable as the months march on.

WATCH OUT FOR THESE

In addition to the previously mentioned exponential rise of wireless internet connectivity, and the exponential rate of miniaturization, there are two other exponential growth rates the IC can only ignore at its--and the nation's--peril, that is, the exponential decline in the cost of computing, and the exponential rise of social software. Let's consider these individually and then taken together.

We are now in the beginning of hi-speed wireless connectivity. This technology is called Wi-Fi. It has a range in the low hundreds of feet. The next generation of connectivity is called WiMAX (Wikipedia 2007e). It has a range of 20 to 30 miles. That is quite a leap. One might say an exponential leap. Plans are to implement WiMAX in the electromagnetic spectrum being vacated by analog television. This has the potential of eliminating the need for the "last mile" internet wires (DSL and Cable) which now is so very expensive to deploy. Once providers set up multiple overlapping transponders, a person can be continuously logged into their own wireless network anywhere around town.

- The implications for ubiquitous continuous connectivity are staggering for the IC. With GPS, there is no place to hide. To go off the grid makes one conspicuous by his/her

absence. (Just who are all those people in Northern Virginia who go "off grid" eight hours a day? I guess we know who to target now!)

We have all seen the "Spock-like" ear pieces people wear for hands-free cell phone conversations. While not in production yet, the new generation ear piece will fit entirely inside the ear, like a hearing aid (Gizmodo 2006). The miniaturization of distortion free, adaptive camera lenses (Ren, et. al. 2006) will allow cell phones to take near-professional quality photographs and movies in the next few years. The exponential miniaturization of memory chips enables huge quantities of data to be recorded locally.

- The implications for miniaturization are frightening. We will soon enter an era when every person will have the ability to have hidden devices that can record continuously the images, audio, and video of their entire life. Covert surveillance will no longer be the exclusive competitive advantage of intelligence and law enforcement. Our targets will record us while we record them--in part because everybody will be recording everything (e.g., Bell and Gemmell 2007).

Cost of computing is decreasing exponentially, and will continue to do so for at least the next 40 to 50 years. Kurzweil (2005, p.69) shows the exponential decrease in the cost of computing from the hand-cranked calculators of 1910 to the desktop PCs of 2000, with several projections for the next 20 years. What that means is that the same computing power costs much less over time. In the desktop computing market, rather than delivering the same computing power at less cost, more computing power is delivered at the same cost. In other markets, however, the low

cost of computing means that computational components are embedded into devices previously built without computation--watches, toasters, thermostats, cars, office building door locks, etc.

- The implications for the declining cost of computing are astounding. Applying more compute power to certain problems makes them more tractable, like voice to text and text to voice. We have all had simple conversations on the phone with a computer that asks us questions and interprets our vocal responses. This is just the beginning. Very high capacity computing platforms will be able to search images, audio, and sound. The ability to submit a photograph to a search engine and have it respond with a rank ordered list of probable names is just now moving from research to production (IBM 2007).

The rise of social software in the last five years has been truly amazing. The most notable examples are Flickr for picture sharing, YouTube for video sharing, LinkedIn for resume sharing, MySpace, Facebook, and Second Life for friendship sharing, Twitter for activity sharing, and Wikipedia for knowledge sharing. All of these are experiencing exponential growth. Except for Wikipedia--in the form of the Intellipedia--no analogs of these services currently exist on the classified networks. We are at least one generation behind and are starting to lag into our second generation.

- The implications for the rise of social software are profound for the intelligence community. The contestants on "Who Wants to be a Millionaire" (www.millionairetv.com) are much smarter when they tap into their network for answers, than they are by themselves. In a similar fashion, LinkedIn has the ability to ask a

question of one's network, and get responses back within minutes. Again, for a community in the business of outsmarting our enemies, ignoring the powerful effect of multiplicative smartness gained through the use of social software is unbelievable.

Combining these four exponential trends gives rise to a new world that--for the linear thinkers among us--will seem to appear out of nowhere. As a prelude, we introduce JOTT.com. JOTT will receive a phone call from a subscriber and then transcribe the message into text and deliver that text as an email to a person of choice. Not only that, a person can call a message into JOTT and it will convert it to text and post it on that person's blog--voice to text to blog.

- Consider this first scenario: a person is listening to a lecture. The speaker uses the word "haptics." The person, using their in-ear cell phone, whispers to JOTT to send the word "haptics" to the (interactive) Wikipedia. The Wikipedia would send the text of the article on "Haptics" back to a (reverse) JOTT, which translates the text to speech and then calls the person and speaks the answer. One could replace the interactive Wikipedia with a LinkedIn query and tap the human network in real time.

- Now a second scenario: a person turns on the record button on their computerized cell phone. They activate the voice stress analyzer. The computerized cell phone will send beeps to the in-ear transceiver when the stress in the voice exceeds a certain threshold.

- Now a third scenario: a person takes a telephoto picture of a person with their cell phone and uploads the picture to a multi-image search engine which searches MySpace,

FaceBook, Flickr, YouTube, and Google for other occurrences of similar pictures and returns that name most closely associated with that picture.

- One final scenario: an IC human resource officer happens to be traveling in Bahrain when a coup goes badly wrong. The officer is able to use her miniaturized, computerized, wireless cell phone to video the escape car. From the street, the officer uploads the video along with a short text description to an IC classified "YouTube" site. The officer also puts alerts out to her classified "Facebook" network. They mobilize internal resources to alert concerned US interests. Headquarters sends redeployment instruction back to the officer in the street within 20 minutes. She makes her travel arrangements via cell phone while on route to the airport.

APPLICATION TO THE IC

The National Intelligence Strategy (DNI 2005), the 100-day plan (DNI 2007), and the subsequent 500-day plan (not yet publicly published) all place great emphasis on improving collaboration within the intelligence community, and correctly so. It is one of the pillars of a 21st Century Intelligence Community. Within the Intelligence Community context collaboration is most often defined as information sharing among agencies. This is a good linear direction and we should get on with it.

- We desperately need the automated ability for individual officers to share text, sound, images, and video from unclassified platforms to IC-wide classified platforms. Putting

up classified equivalents of such social software as iTunes.com, Flickr.com, Youtube.com, Facebook.com, Slideshare.net, and Wikisource.net is long, long overdue.

Unfortunately, information sharing will be completely overtaken by exponential growth curves over the next five to seven years. Sharing information is sharing our past. Once our information is codified into sharable databases, it is what we knew when we codified it. It is history. We need to share our present.

- We share our present when we share--not our data--but our thinking minds. We need to bring our collective human brilliance to bear on current problems in real or near-real time. The intelligence community should learn the lesson of Net-centric Warfare (Wikipedia 2007f). When there are continuous n-way wireless connections among the planners, the targeteers, and the combatants, the resultant solutions are superior by orders of magnitude.

The problems facing the IC in the 21st century are too difficult for a single person or for small groups to solve. We need to not only connect with other members of the IC in real-time, but also with citizens who have deep knowledge and extraordinary insights. As Bill Joy, the co-founder of Sun Microsystems, has said, "The smartest people don't work for you, so if your company really wants to innovate, it's going to need help from the outside world" (Computer Weekly 2001). It is the only way for our community and nation to survive in the 21st Century.

- The IC must create the ability of our officers to stay connected wirelessly as they move in and out of our buildings, transit the nation, and travel around the world. This will require our mission managers, our security officers, and our IT professionals to work toward solutions at an exponential rate. We cannot perform our primary mission--securing our nation--with anything less.

CONCLUSION

This paper presents a conservative view of the impact of exponential growth resulting from a few technological areas. Some more expansive thinkers, as they examine the effect of synthesizing many exponential growth curves (economic, technological, social), conclude that a truly unimaginable change will happen in about 20 years (Vinge 1993, Kurzweil 2005).

Exponential growth rates in current technologies are real. They will have profound and far-reaching effects on the way the people of the world behave. The human ability to share data and insights from wherever we are on the globe is fast becoming the norm. As the IC moves along in a linear fashion, the rest of the world will appear to have leaped forward from out of nowhere. We are already behind and in order to survive we must run ever faster.

We can start by:

- deploying infrastructure to allow all IC officers to post information (text, image, audio, video) on high-side classified information sharing sites from the open Internet.
- adopting policies, procedures, and devices to allow our officers to be wirelessly connected to each other and to our information regardless of geographic location.

The Red Queen is inviting us to dance. Will we?

REFERENCES

- Carroll, Lewis (1865), Alice's Adventures in Wonderland. London: Macmillan. Full text of the Millenium Fulcrum Edition 3.0 is available from http://www.gutenberg.org as "alice30.txt."

- Carroll, Lews (1872), Through the Looking Glass. London: Macmillan. Full text of the Millenium Fulcrum Edition 1.7 is available from http://www.gutenberg.org as "lglass19.txt."

- Census Bureau (2007), "Historical Statistics: Selected Communications Media" in The 2007 Statistical Abstract. http://www.census.gov/compendia/statab/hist_stats.html (accessed 03 September 2007).

- Computer Weekly (2001). "Sun unleashes P2P protocol" at the Computer Weekly website. http://www.computerweekly.com/Articles/2001/06/20/180966/sun-unleashes-p2p-protocol.htm (accessed 13 September 2007).

- Bell, Gordon and Jim Gemmell (2007), "A Digital Life" in Scientific American, March 2007. http://www.sciam.com/print_version.cfm?articleID=CC50D7BF-E7F2-99DF-34DA5FF0B0A22B50 (accessed 08 September 2007).

- Birch, David and Devis Grebu (1988), The King's Chessboard. New York: Puffin Books. http://books.google.com/books?id=HsiIAAAACAAJ

- Director of National Intelligence (2005), National Intelligence Strategy. http://www.dni.gov/publications/NISOctober2005.pdf (accessed 08 September 2007).

- Director of National Intelligence (2007), 100 Day Plan for Integration and Collaboration. http://www.dni.gov/100-day-plan/100-day-plan.pdf (accessed 13 September 2007).

- Feynman, Richard (1959), "Plenty of Room at the Bottom" at California Institute of Technology. http://www.its.caltech.edu/~feynman/plenty.html (accessed 08 September 2007).

- Gizmodo (2006), "Micro Bluetooth Earpiece: Smaller Than a Dime, Spytastic, Handmade" at The Gizmodo Website. http://gizmodo.com/gadgets/micro/micro-bluetooth-earpiece-smaller-than-a-dime-spytastic-handmade-194986.php (accessed 08 September 2007).

- Human Genome Program (2007), Human Genome Project Website. http://www.ornl.gov/sci/techresources/Human_Genome/home.shtml (accessed 07 September 2007).

- IBM (2007), Query by Image Content (QUBIC) Website. http://wwwqbic.almaden.ibm.com/ (accessed 08 September 2007).

- Infocom Development Authority (2007), iDA Website. http://www.ida.gov.sg/Programmes/20061027174147.aspx?getPagetype=36 (accessed 07 September 2007).

- IRRI (2007), World Rice Statistics, Table 1. http://www.irri.org/science/ricestat/pdfs/Table%2001%20Rice%20Production,%20Area%20and%20Yield.pdf (accessed 25 July 2007).

- Kurzweil, Ray (2001), "The Law of Accelerating Returns" at KurzweilAI.net. http://www.kurzweilai.net/articles/art0134.html?printable=1 (accessed 03 July 2007).

- Kurzweil, Ray (2005), The Singularity is Near. New York: Viking. http://books.google.com/books?id=88U6hdUi6D0C

- Ren, Hongwen, David Fox, P. Andrew Anderson, Benjamin Wu, and Shin-Tson Wu (2006), "Tunable-focus liquid lens controlled using a servo motor" in Optics Express, 4 September 2006, Vol. 14, No. 18. Available at http://www.holochip.com/technology/pdf/Opt_Express_Ren_liquid_lens.pdf (accessed 08 September 2007).

- Songfa, Shi (1995), "Development of Rice–Fish Farming in Guizhou Province" in IDRC Books Free Online. http://www.idrc.ca/en/ev-27637-201-1-DO_TOPIC.html (accessed 25 July 2007).

- Vinge, Vernor (1993). "The Coming Technological Singularity: How to Survive in the Post-Human Era." San Diego State University. http://www-rohan.sdsu.edu/faculty/vinge/misc/singularity.html (accessed 18 July 2007).

- Wikipedia contributors (2007a), "Ambalappuzha Sri Krishna Temple," in Wikipedia, The Free Encyclopedia. http://en.wikipedia.org/w/index.php?title=Ambalappuzha_Sri_Krishna_Temple&oldid=142086084 (accessed 23 July 2007).

- Wikipedia contributors (2007b), "Sigmoid function," in Wikipedia, The Free Encyclopedia. http://en.wikipedia.org/w/index.php?title=Sigmoid_function&oldid=151213901 (accessed 03 September 2007).

- Wikipedia contributors (2007c), "Bethlehem Steel," in Wikipedia, The Free Encyclopedia. http://en.wikipedia.org/w/index.php?title=Bethlehem_Steel&oldid=154419373 (accessed 07 September 2007).

- Wikipedia contributors (2007d), "IBM," in Wikipedia, The Free Encyclopedia. http://en.wikipedia.org/w/index.php?title=IBM&oldid=156266165 (accessed 07 September 2007).

- Wikipedia contributors (2007e), "WiMAX," in Wikipedia, The Free Encyclopedia. http://en.wikipedia.org/w/index.php?title=WiMAX&oldid=156233702 (accessed 08 September 2007)

- Wikipedia contributors (2007f), "Network-centric warfare," in Wikipedia, The Free Encyclopedia. http://en.wikipedia.org/w/index.php?title=Network-centric_warfare&oldid=156703835 (accessed 13 September 2007)

- Wireless Philadelphia (2007), Wireless Philadelphia Website. http://www.wirelessphiladelphia.org (accessed 07 September 2007).