NASA (Pat Izzo)

NASA Center for Climate Simulation "Discover" supercomputer contains 15,000 processors

TECHNOLOGICAL STRATEGY IN THE AGE OF EXPONENTIAL GROWTH

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There can be little doubt that the definitive technological strategy problem at this time is how to deal with exponential growth in digital technologies. Exponential growth is producing effects that are pervasive across the global industrial base and having an impact on almost every aspect of developed societies in both constructive and destructive ways. While exponential growth is producing important changes in how societies and their respective militaries function, technological strategies underpinning the definition and development of contemporary weapons systems are frequently not well aligned with the seismic growth in the basic technologies employed in such systems. Whenever the evolution of a technology base outstrips technological strategy and operational technique, there is potential for disaster in battle. Excellent case studies exist where formerly new weapons were deployed and used without a well-defined technological strategy or commensurate conceptual coupling with tactics, operational technique, and theater-level strategy, resulting in difficulties and often failure.

Exponential growth in digital technologies used for information-gathering, processing, storage, and distribution is arguably the defining trend in this decade, yet it is frequently not well understood. Some observers regard such growth with unbounded optimism.[1] A common misconception is that exponential growth is pervasive, but this is seldom true. Even within rapidly evolving areas, exponential growth may be limited to a small number of constituent components in larger systems.

To appreciate the manner in which exponential growth affects technological strategy, the inevitable starting point is to determine how exponential growth works, and which technologies grow exponentially and which do not. Only then is it possible to divine the broader and deeper implications of the problem and its concomitant effect on technological strategy, operational strategy, and ultimately, grand strategy.

This article explores the social and technological effect termed *exponential growth*, contemplates how it affects military systems and technological strategy, and considers a number of related problems in aligning technological strategy with an exponentially growing technology base.

Exponential Growth Laws

The term *exponential growth* describes an observed effect in some basic technology, where performance per dollar multiplies over time. The best known example is Moore's Law, under which the density of microprocessors doubles over an 18- to 24-month period.[2] The behavior observed is, in mathematical terms, no different to that observed in continuously compounded interest in finance. The gains experienced in one time interval set the starting point for the next. As a result, the gains are continuous and can be enormous over periods of time. Moore's Law presents the best example in recent times where computing power in handheld devices now matches or exceeds that of the largest computer systems built and used during the 1960s at costs which are trivial in comparison with their predecessors.

In practice, exponential growth is seldom sustained indefinitely and usually ceases when some bounding condition, determined by physics or mathematics, is encountered, or when research and development funding collapses due to shifts in a commercial marketplace or government funding priorities.

An important observation is that unlike many laws in hard science, which have a basis in mathematics and physics, "exponential growth laws" have no such basis and represent an empirical generalization of the observable interaction of technology and social behavior. Unlike laws in hard sciences, which are immutable, exponential growth laws may collapse at any time if the social conditions producing them change.[3]

In recent decades, the sustained exponential growth in digital technologies used for information-gathering, processing, storage, and distribution shows that the market for consumer and industrial digital equipment has yet to saturate, and key physics bounds have yet to be encountered.

Nonexponential vs. Exponential Growth

Nonexponential growth is the more common situation across the technology base. This is important because most military systems comprise many components, few of which will grow exponentially. Technologies that are mechanical or chemical, such as structural materials, aerodynamics, hydrodynamics, and all forms of propulsion, do not exhibit exponential growth because the underlying physics do not permit it.

While we have seen strong improvements in jet and rocket propulsion since their advent in modern military systems during the 1940s, jet engine fuel efficiency has improved over that time by a factor of three at best, while rocket propellants have improved in specific impulse only by a slightly better margin. Improvements in structural materials, either in weight or strength, have also been on a similar scale over a half-century of continuous research and development. Much the same can be said of chemical explosives, armor materials, and many other pivotal technologies used in military systems.

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A common misconception is that computer software grows exponentially in performance over time. While software has shown evidence of exponential growth in raw complexity, this is typically at the expense of computational efficiency and thus the speed with which a computation can be performed.

When considered against the technology base in military use today, technologies with exponential growth behavior are uncommon. Even so, they have forced significant changes and will continue to do so.

Exponential Growth in Computing Technology

Computer hardware is at the heart of the information age and pervades all digital technologies used for information-gathering, processing, storage, and distribution, often in ways not obvious to the casual observer. Whether we look at embedded computers in military equipment, consumer devices of all shapes and sizes, or traditional desktop and server computers used for data processing, at the heart of all of these devices are one or more processor chips—each a single-chip computer. Nearly all processor chips exhibit growth following Moore's Law, and with a half-century of empirical data to prove it, Moore's Law has become a defining driver for planning within the computer industry.

Moore's Law exists because the technology used to fabricate processing chips, whether based on silicon or other more advanced materials, is centered in photolithography, which is used to sculpt the features that form the transistor switches within the chip, permitting the fabrication of ever smaller transistors over time


Chief of Naval Research addresses Naval Science, Technology, Engineering and Mathematics Forum

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as photolithographic technology improves. Smaller transistors typically switch faster, dissipate less power, and permit more complex internal structures on the chip.[4]

Until recently, Moore's Law tracked true both for the density of processors and for how quickly they could execute, producing exponential growth in chip density and switching speeds. The actual improvements in computing performance were frequently better than exponential, as increasingly sophisticated performance improving architectural features could be employed. A reality little appreciated outside the computer architecture community is that a contemporary processor chip in an iPhone, notebook, or iPad/Kindle has an internal architecture not unlike a mainframe or supercomputer of the 1960s or 1970s.

The technology base, however, is approaching the limits of photolithographic techniques. At this time, internal heat dissipation is putting limits on how fast processors can switch internally. This has resulted in the increasing use of multicore or parallel processors where a single chip hosts two, four, six, or many more processors or cores, rather than a much faster single core. More important, transistor sizes are approaching the limits of what physics permits and where quantum physical effects begin to impair operation. Current estimates by the industry suggest that Moore's Law, using photolithographic fabrication techniques, may hit hard limits within 5 to 15 years, assuming no significant physics breakthroughs in other areas.[5] To place this in perspective, a rule of thumb in science-based futures predictions is that reliable estimates more than 11 years into the future are scarce because unexpected breakthroughs can and often will result in unpredicted outcomes.[6] Therefore, it is possible that unexpected and intractable obstacles may be encountered later or sooner than current estimations.

Unfounded Optimism in Parallel Processing

When a processor is not fast enough to solve a problem, the most common solution is to employ more than one processor—a technique known as parallel processing whereby the computing workload is split across multiple processors. Unfortunately, not every type of computation can be easily split up to permit faster computation. The optimism surrounding the use of computational clouds and other highly parallel systems is frequently unrealistic, as such systems will not realize any performance gain if the problem to be solved does not "parallelize" readily. This has been understood by computer scientists since Gene Amdahl published his now famous 1967 paper.[7]

When Moore's Law eventually plateaus, the fallback strategy of aggregating vast numbers of processing cores to improve performance will only produce effect for some types of computations. In many applications, Amdahl's Law will present an intractable obstacle to further performance growth.

Exponential Growth in Storage Technology

Storage technologies are in many respects as important as processing technologies in many military applications. Currently, this area is dominated by three technologies: encompassing semiconductor memories, rotating magnetic "hard" disks, and rotating optical disks, such as the CD-ROM and DVD. All of these technologies have exhibited strong and sustained exponential growth in storage density, comparable to or stronger than seen in processing chips.

Semiconductor memories such as modules used in computers, nonvolatile flash memories used in USB thumbdrives, and digital camera SDHC cards all follow Moore's Law and will closely track growth in processor technology. Rotating magnetic hard disks follow Kryder's Law, with strong sustained exponential growth in recent years. Similar growth is observed in optical storage technologies.[8] While data storage density has been strongly exponential, access times, or how long it takes to find an item of data, have not been. The mechanical nature of rotating media has at best seen access times halved over the last two decades. While the use of semiconductor cache memories on such drives has much improved access times for frequently used data, infrequently used data will continue to suffer the speed limitations imposed by mechanical designs ever since the 1960s.

Exponential Growth in Networking Technology

Networks have been a central part of the explosive growth seen in information technologies over the last two decades and indeed have been a prominent feature of the high operations tempo paradigm of network-centric warfare (NCW). In fixed cabled networks, especially those using optical fibers, growth has been exponential due in part to the enormous bandwidth of optical fiber and in part to the photolithographically fabricated semiconductor laser chips employed. In such networks, exponential growth will continue until hard limits are encountered in laser fabrication.

The performance of wide area wireless radio networks, pivotal in military systems, is generally not growing exponentially in throughput performance and never will. Many advocates of NCW appear to have assumed otherwise. While Edholm's Law argues for exponential growth in wireless technologies such as WiFi and WiMax, it fails to consider the critical constraint of transmission range, a central need in military networks.[9]

The dichotomy between cabled optical networks and wireless radio networks reflects the different transmission physics that apply to guided versus unguided transmission media.[10]

Radio frequency transmission effects thus impose much stronger limitations on data throughput than the density of the chips in the equipment used within the link or the network. Increasing congestion across the radio frequency spectrum presents further difficulties, which will not be overcome easily. Another problem unique to military radio networks is resilience to hostile jamming, always at the expense of data throughput.

Exponential Growth in Optical and Radio Frequency Sensor Technology

Digital imaging chips have produced a revolutionary impact in consumer and professional photography, as well as military intelligence, reconnaissance, and surveillance (ISR) applications. No differently, MMIC (Monolithic Microwave Integrated Circuit) technology has produced similar effects in consumer wireless products, as well as military radar and passive radiofrequency sensors. Both technologies, fabricated using the same photolithographic techniques as processor chips, have exhibited exponential density growth, but much slower than that observed in processors and memories.

The more sedate growth observed is an inevitable byproduct of the need to accommodate unique design constraints, such as photosite performance in optical chips or electrical impedance matching in MMICs. These constraints are frequently much stronger than gains arising from density improvement.

The Nonexponential Realities of Software Algorithms

Computer algorithms used in software do not commonly display exponential performance growth and, given the mathematical realities involved, never will. The observed improvements in performance are mostly asymptotic, where progressive refinements over time push the performance of the algorithms ever closer to some fundamental mathematical limit in ever smaller increments. Prima facie, this would suggest that overall performance of hardware and software should improve exponentially over time as hardware performance tracks Moore's Law. The reality is otherwise.

The most pronounced effect we see in software performance over the last three decades is the "bloatware problem," where software progressively grows in complexity over time, soaking up any gains in hardware performance, often at rates faster than exponential growth in hardware can accommodate.[11] Such complexity growth is endemic in both civilian and military software products, whether intended for office or real-time embedded applications. The causes are partly accidental and partly essential.[12]

Accidental complexity and its growth is partly the byproduct of attempting to maintain compatibility with legacy software and hardware interfaces and data formats while accommodating new interfaces and data formats, as well as new features and operating modes. In a sense, this effect is akin to increasingly complex DNA in evolving biological organisms—adaptation requires growth in complexity. Essential problems in software development relate to the problem being solved, encompassing the complexity of the problem, and the typically asymptotic behaviors of algorithms.

Far more problematic, however, are the other accidental causes of growth, which more often than not reflect undisciplined requirements by customers and vendors alike. Whether a commercial product is being dressed up with features to expand its market footprint, or a military system is being overfeatured to satisfy the wish lists of multiple stakeholders with diverse agendas, the effect is the same, and the problem is rooted in human social behavior rather than technology.

This problem has been understood for decades, yet no common solution has been devised to overcome it. The competitive internal dynamic of groups defining designs, or implementing them, is at the root of the problem. Individuals seek to improve the product or attach their personal signature to it by adding to it, a problem arising in product definition and/or development. For the foreseeable future, the outlook for improved military software applications performance is not good, as the primary cause of the bloatware problem is rooted in the internal social dynamics of organizations rather than in any basic technology. In this respect, the power of software to be rapidly adapted becomes a weakness in its own right.

Impact of Exponential Growth and Evolutionary Strategies

Exponential growth produces positive and negative effects. In digital technologies used for information-gathering, processing, storage, and distribution, it has produced its greatest positive impact in ISR applications and military communications and networking. Other areas have also seen major positive impacts, such as navigation systems, weapons guidance, vehicle control and management systems, and, most recently, directed energy weapons.

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The most common negative effect is the premature obsolescence of digital processing chips embedded within weapons systems, forcing frequent hardware upgrades and often expensive software changes to maintain the supportability of the equipment. Where not addressed properly, this has significantly contributed to the life-cycle costs of maintaining and operating equipment.

Positive effects are typically produced in two distinct ways. The first and most frequent is by a linear evolution strategy, where the performance, capability, compactness, reliability, or functionality of some existing system or subsystem is improved or enhanced by replacement of a legacy technology with an exponentially growing new technology. It is termed *linear*, as the growth follows an earlier direct or linear evolutionary pattern in the technology.

The second and less frequent way in which exponential growth produces impact is through *lateral* evolution strategy, where new technology presents opportunities to devise entirely new solutions to longstanding, or entirely new problems, reflecting the Edward de Bono model of "lateral thinking."[13] Lateral evolution can frequently produce highly disruptive effects, as the new solution will often exploit systemic weaknesses in an opponent's capabilities that cannot be easily overcome by established means.

There is an abundance of good case studies to be considered. Linear evolution includes the use of monolithic chips in visible band and infrared imaging systems, where

U.S. Army (Jennifer Spradlin)

Netherlands air force pilot checks RecceLite tactical reconnaissance pod at Kandahar Airfield, Afghanistan, prior to mission

smaller, more sensitive, more reliable, and higher resolution sensors have yielded revolutionary improvements against legacy wet film technology. The advent of Gallium Arsenide radio frequency chips for use in radar has seen revolutionary improvements in the transition from legacy mechanically steered radar and communications antennas to contemporary Active Electronically Steered Array (AESA) antennas. Three recent case studies of lateral evolution are worth careful consideration, as they show how a shift in basic technology becomes an enabler in areas that were not even considered when the new technology was developed.

The first case study considers the emergence of gigapixel imagers, such as the Defense Advanced Research Projects Agency/BAE System Autonomous Real-Time Ground Ubiquitous Surveillance Imaging System, which aggregates hundreds of consumer commodity megapixel-class cell phone imaging chips to permit simultaneous wide angle, high-resolution imaging of large areas. The designers of these cell phone camera chips had no conception of the military potential of the devices. Yet the technology has significant long-term potential across a wide range of ISR applications, not only in counterinsurgency environments.[14]

The second case study focuses on the use of high power AESA radars to produce radio frequency weapons effects intended to disrupt or electrically damage opposing aircraft or guided weapon sensors or systems. The availability of high-peak power emissions in larger AESA radars became the enabler for this technique, which has considerable long-term potential given the established trends in AESA design.[15]

The third case study concerns the use of solid-state laser diodes and doped optical fiber amplifier technology, both initially developed for communications applications as optical pump technology for electrically powered high-power laser weapons. Both of these technologies have been adapted to develop pumping sources for laser weapons that overcome the historical "magazine depth" problem associated with chemically pumped lasers that depend on the in situ chemical propellant supply.

All of these case studies present capability surprises to opponents of the United States that will significantly complicate their operations in combat situations and demonstrate the highly disruptive effects that can be produced by lateral evolution.

Technological Strategy and the Technological Strategist

The discipline of technological strategy has been part of warfare for millennia but was without doubt most actively practiced during the Cold War when the United States confronted a technologically competent and often highly creative peer competitor in the Soviet bloc. The seminal work on modern technological strategy dates back to the most intensive phase of that contest during the latter 1960s.[16]

Technological strategists use advanced technology to outmaneuver and often economically defeat opponents by forcing disproportionate expenditures in peacetime and disproportionate attrition in wartime. Most technological strategists are gifted scientists or engineers by training with a talent for strategic thought and considerable natural creativity.

While technological strategy is not a strong feature of contemporary Western defense planning, it remains a central feature of highly successful corporate players within the electronics and computing industries. The astounding resurgence of Apple, via its innovative Mac, iPod, iPhone, and iPad product families, represents without doubt the best recent commercial case study, an effort that was largely driven by Steve Jobs, who was both a gifted engineer and a strategic thinker.[17]

It is abundantly clear that technological strategy can be explained, codified, and systematically taught. However, the historical record suggests that genuine breakthroughs require a strong element of talent and vision. As a result, a fundamental challenge to most organizations is that the talent required to produce outstanding results in technological strategy tends to be scarce and must be nurtured and developed.

Effective technological strategists must have deep expertise in the technological areas of interest, considerable experience to know what can and cannot be built, and an understanding of what will and will not work operationally. They must also possess the gift for strategic thought. Accomplished past practitioners across the Western defense industry include Vickers's Barnes Wallis, who devised the modern bunker-busting bomb, Lockheed's Kelly Johnson and Northrop's John Cashen, and within the Armed Forces the often controversial yet gifted Colonel John Boyd, who was able to articulate and effectively propagate his revolutionary vision of energy maneuverability.

The inevitable consequence of failing to practice good technological strategy is that opponents will produce breakthroughs. A smart opponent will produce repeated "capability surprise" events to an advantage, as the United States did to the Soviet Union, contributing crucially to the eventual bankruptcy of the Soviet bloc.

Technological Strategy vs. Exponential Growth

The presence of exponential growth in key current technologies is a double-edged sword because these technologies have been commodified and are globally accessible in the commercial marketplace. A Russian or Chinese weapons developer will have access to much of the same basic technology as his peers in the United States. This represents a leveling of the technological playing field unseen since World War II. For instance, the well-developed Russian technological strategy intended to defeat U.S. airpower is disciplined and well-considered, leverages exponential growth in key technologies, and displays a deep understanding of critical ideas and how to leverage globalized exponentially growing technologies.[18]

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On a level playing field, with exponential growth in critical technologies, the player who can best exploit talent to an advantage—all else being equal—will inevitably win. For the United States and its technologically competent allies, this period should be one of critical reflection. Many recent high-profile programmatic failures display numerous symptoms of poor practice and implementation of technological strategy during program definition and later development, beginning in the decade following the end of the Cold War. Moreover, poor understanding of exponential growth and concomitant early component obsolescence has contributed to severe life-cycle cost problems across a wide range of programs.

A good case can be made that these failures directly reflect the diminished role of technological strategists in the post–Cold War environment, where imperatives other than defeating peer competitor nation-states became ascendant and dominant, while the last generation of Cold War–era technological strategists progressively retired from government service or retired altogether, with few if any replacements trained or appointed.

While entities such as the Defense Science Board and respective Service science boards and chief scientists have remained active in technological strategy and continue to provide valuable inputs, all of these entities perform roles that are essentially advisory rather than serving as directly integrated and organic components of the capability development cycle, where technological strategists were most active during the Cold War.

In a period of exponential growth in many critical technologies, maintaining an advantage over nascent technological peer competitors requires that technological strategy be a tightly integrated component of the capability development cycle and that an ample population of gifted technological strategists exists both within government organizations and within the contractor community. If the United States wishes to retain its primacy in modern nation-state conflicts, technological strategy must be restored to the prominence it enjoyed during the Cold War period. **JFQ**

NOTES

[1] The best example is Ray Kurzweil's *The Singularity Is Near: When Humans Transcend Biology* (New York: Viking, 2005). Kurzweil's "singularity" is a projected future point in time where machine intelligence exceeds human intelligence. While the science underpinning Kurzweil's projections is frequently weak, his work has stimulated important ethical, philosophical, and strategic arguments about how to manage advanced artificial intelligence.

[2] Gordon E. Moore, "Cramming More Components onto Integrated Circuits," *Electronics*, April 19, 1965, 114–117.

[3] In a strict scientific sense, exponential growth laws should not be called "laws" but rather "curves." A more exact model is that these laws are convolutions of multiple S-curves for specific technologies employed. See Murrae J. Bowden, "Moore's Law and the Technology S-Curve," *Current Issues in Technology Management* 8, no. 1 (Winter 2004).

[4] Carver Mead and Lynn Conway, *Introduction to VLSI Systems* (Reading, MA: Addison-Wesley, 1980).

[5] R.W. Keyes, "Fundamental Limits in Digital Information Processing," *Proceedings of the IEEE* 69, no. 2 (February 1980), 267–278; R.W. Keyes, "Fundamental Limits of Silicon Technology," *Proceedings of the IEEE* 89, no. 3 (March 2001), 227–239; K.K. Likharev, "Classical and Quantum Limitations on Energy Consumption in Computation," *International Journal of Theoretical Physics* 21, no. 3–4 (May 1982), 311–326; V.V. Zhirnov et al., "Limits to Binary Logic Switch Scaling: A Gedanken Model," *Proceedings of the IEEE* 91, no. 11 (November 2003), 1934–1939; and Laszlo B. Kish, "End of Moore's Law: Thermal (Noise) Death of Integration in Micro and Nano Electronics," *Physics Letters A* 305, no. 3–4 (December 2002), 144–149.

[6] J. Birnbaum, "The Next 50 Years," ACM97 Conference Talks, Association for Computing Machinery, 1997.

[7] Gene M. Amdahl, "Validity of the Single Processor Approach to Achieving Large Scale Computing Capabilities," from the proceedings of the April 18–20, 1967, spring joint computer conference, AFIPS 1967 (Spring), 483–485, New York, NY, 1967.

[8] Chip Walter, "Kryder's Law," *Scientific American*, July 25, 2005.

[9] Steven Cherry, "Edholm's Law of Bandwidth," *IEEE Spectrum*, July 2004.

[10] Unguided media depend on antenna design, radio propagation through the atmosphere, hostile radio frequency jamming, emission stealthiness, and Shannon's information theory. See R.C. Hansen, "Fundamental Limitations in Antennas," *Proceedings of the IEEE* 69, no. 2 (February 1981), 1934–1939; R.K. Crane, "Fundamental Limitations Caused by RF Propagation," *Proceedings of the IEEE* 69, no. 2 (February 1980), 196–209; and C.E. Shannon, "A Mathematical Theory of Communication," *Bell System Technical Journal* 27 (July, October 1948), 379–423, 623–656.

[11] Niklaus Wirth, "A Plea for Lean Software," *Computer* 28, no. 2 (February 1995), 64–68; and Joel Spolsky, "Strategy Letter IV: Bloatware and the 80/20 Myth," March 23, 2001, available at <www.joelonsoftware.com/articles/fog0000000020.html>.

[12] Frederick P. Brooks, Jr., "No Silver Bullet: Essence and Accidents of Software Engineering," *Computer* 20, no. 4 (April 1987), 10–19.

[13] Edward de Bono, *The Use of Lateral Thinking* (London: Cape, 1967).

[14] Graham Warwick, "ARGUS: DARPA's All-Seeing Eye," February 10, 2010, available at <www.w54.biz/showthread.php?138-BAE-Persistent-Surveillance-System>.

[15] See, for instance, D.A. Fulghum, "Hornet's Electronic Sting," *Aviation Week & Space Technology*, February 26, 2007, 24–25.

[16] Stephan T. Possony et al., *The Strategy of Technology* (1970), available at <www.jerrypournelle.com/slowchange/Strat.html>.

[17] Richard Gourlay, "Strategy: How Steve Jobs Changed the World," *Businesszone*, August 30, 2011, available at <www.businesszone.co.uk/blogs/richard-gourlay/do-you-have-vision-or-are-you-just-dreamer/strategy-how-steve-jobs-changed-wor>.

[18] Carlo Kopp, "Evolving Technological Strategy in Advanced Air Defense Systems," *Joint Force Quarterly* 57 (2nd Quarter 2010), 86–93.