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A Future State for NASA Laboratories—Working in the 21st Century

Jerome T. Kegelman, Charles E. Harris, Richard R. Antcliff, and Dennis M. Bushnell
Langley Research Center, Hampton, Virginia

Douglas L. Dwoyer
Hampton Roads Research Partnership, Newport News, Virginia

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TABLE OF CONTENTS

I. OVERVIEW OF THE 21^{ST} CENTURY LABORATORY (FUTURE LAB)

The name "21st Century Laboratory" is an emerging concept of how NASA (and the world) will conduct research in the very near future. Our approach is to carefully plan for significant technological changes in products, organization, and society. The NASA mission can be the beneficiary of these changes, provided the Agency prepares for the role of 21^{st} Century laboratories in research and technology development and its deployment in this new age. It has been clear for some time now that the technology revolutions, technology "mega-trends" that we are in the midst of now, all have a common element centered around advanced computational modeling of small scale physics. Whether it is nano technology, bio technology or advanced computational technology, all of these megatrends are converging on science at the very small scale where it is profoundly important to consider the quantum effects at play with physics at that scale. Whether it is the bio-technology creation of "nanites" designed to mimic our immune system or the creation of nanoscale infotechnology devices, allowing an order of magnitude increase in computational capability, all involve quantum physics that serves as the heart of these revolutionary changes.

NASA's existing 20^{th} Century research centers are the stewards of over $10B in infrastructure that will consume several billion dollars in maintenance and upkeep during the next two decades. We must begin to plan for the time when this infrastructure will need to be replaced with more relevant infrastructure, in light of the accelerating pace of technology development (Kurzwiel), and begin planning for the 21^{st} Century infrastructure that will replace it.

A few key points should be made about the 21^{st} Century Lab. To be clear, the 21st Century Lab is not a proposal for a new program or project, but rather an attempt to enlighten the reader of the implications of the accelerating pace of technology development and its impact on the future research laboratory. ***The objective of writing this white paper is to stimulate thinking on the nature of a subset of investments and changes that may be initiated today in preparation for the inevitable changes that will come in the next two decades.*** This paper is not only about infrastructure and facilities, it must include the nature of the workforce and practices by which we will foster breakthrough technologies. Don't expect there to be (ever) a traditional laboratory that we name Langley's "21st Century Lab." Rather, expect us to start working in the "21st Century" mode with far greater networking with global colleagues and expect far greater collaboration with entities outside NASA, i.e., expect many brains at different locations working on the same or closely related problems and at a much higher speed enabled, at its core, by the ubiquitous nature of info-technology.

To appreciate the magnitude of the changes that will happen in the next two decades, it is helpful to look at the changes over the past FIVE decades, which are due to the

ACCELERATING pace of technology development. Pierre Teilhard de Chardin, a French philosopher, was quoted as saying, "No one can deny that a network (a world network) of economic and psychic affiliations is being woven at ever increasing speed which envelops and constantly penetrates more deeply within each of us. With every day that passes, it becomes a little more impossible for us to act or think otherwise than collectively" (qtd. in Smart).

Before looking for specific recommendations or changes, one should look at the charter for this strategic initiative, which is "to assess the impact of the ongoing technology revolutions and the exponentially increasing pace of technology development on future mission systems and research and technology challenges that the Agency is facing and to provide specific guidance for research laboratory and workforce investments." Following some months of deliberation, the deliverable of this effort is this white paper. To get an idea of the pervasiveness of the impact of the information technology changes, consider the words of Jacques Attali:

> "The impact of information technology will be even more radical than the harnessing of steam and electricity in the 19th century. Rather it will be more akin to the discovery of fire by early ancestors, since it will prepare the way for a revolutionary leap into a new age that will profoundly transform human culture" (Attali).

Rapid technology advances are happening all around us today. Whether we look back over a few years or many decades, we find evidence of the accelerating pace of technology development. NASA must not stand by and watch these changes, but rather, NASA needs to get on board and get out in front of this change. There are six elements that are undeniably changing the work we do and how we do this work. These are described below.

Advancements in Computing Tools, Speed, and Cost

In 1986, IBM PCs were becoming common, and the Macintosh was just introduced, which included an 8 MHZ 16-bit Processor and a 40MByte Hard Drive. During this time frame, a 32-bit MicroVAX was all the rage in laboratory computing. Now, the current version of a Macintosh (64 "Intel" bit-dual processor) is 20,000 times faster, with 8,000 times the storage capacity. We are simultaneously experiencing a rapid maturation of our physics-based design tools and the affordable and ever-faster computing capacity for the application of those tools to complex problems. These tools include, but are not limited to, flow physics, flight dynamics, structures and materials, thermodynamics, and airspace system infrastructure. The tools are based on the principles of classical (Newtonian) physics and loosely the general theory of relativity, but not on quantum theory. The 21st Century Laboratory will be an environment, both physically and virtually, where these tools are advanced, integrated, validated, and applied to problems of significance to the Agency.

Advancements in Materials Science

Recent advances in materials science, specifically advances in nanotechnology, hold the promise of changing everything we know and do with respect to composition, design, and manufacturing of materials. These materials, already under development, have the promise of increasing strength-to-weight ratios by several orders of magnitude greater than those in practice today. These materials can also be designed to include electromagnetic, quantum, or biological functions, including super conductivity, superior insulating properties, immune system enhancing properties and other, multifunctional properties. As this technology is just beginning to blossom, it has been included as one of our revolutionary challenges (Lerner).

Advances in Biological Sciences

The emerging discipline of Bioengineering is advancing very rapidly as well. There have been significant advances in healthcare, agriculture, biofuels and environmental pollution. Great improvements and many discoveries have been made in biologically engineered and produced molecules for human benefit (such as insulin). "By the end of the 21st century," writes Reason magazine science editor Ronald Bailey in his book "Liberation Biology," "the typical American may attend a family reunion in which five generations are playing together. And great-great-great grandma, at 150 years old, will be as vital ... as her 30-year-old great-great grandson with whom she's playing touch football" (qtd. in Smith). While this may be too much for some to believe, it is not that far fetched according to several prominent futurists.

Recent advances in neural science have recently made progress with identifying specific connections by neural transmitters, which hold the promise of allowing specific control of prosthetic devices. These devices can be made specifically controllable by the patient, who can now have heptic sense ("Johns Hopkins's APL and DARPA's Mechatronic Process").

Bioscientists are studying how food production is being altered by the biotechnology revolution, concluding that the "industrialization" of livestock production has changed the way we produce agriculture profoundly. The introduction of genetically modified crop products has been completely taken over by private sector firms, and has completely changed the traditional, 'government sponsored' agriculture research model of the recent past. The model of using private funded research and development has successfully led to the introduction of genetically modified products for over a decade, since the 1993 introduction of Bovine Somatotrophin Hormonr (BST) for dairy cows.

The development of Butanol, a 4-carbon alchohol, yields a 25 percent increase in harvestable energy. It has only CO_2 as a product of combustion, so without SOX, NOX, or Carbon Monoxide, it is considered by some as environmentally "Green." As it is far less corrosive than ethanol, it can be shipped and distributed through existing pipelines. With four more hydrogen atoms than ethanol, is has a higher energy output than ethanol and can be used in fuel cells. A new process has been developed using continuous immobilized cultures of Clostridium tyrobutyricum and

Clostridium acetobutylicum to produce an optimal butanol productivity of 4.64 g/L/h and a yield of 42 percent (Ramey).

Changes in World Demographics

There are undeniable changes in world demographics that are having a profound influence on our world, as in the advances made in China and India. India has about 1/6th of the world's population, while it has only 2.4 percent of the world's land area. China is the world's largest population, with about 1.2 billion people. It is profoundly clear that the burgeoning middle classes of these two countries are beginning to represent a significant change in the global economy. Both India and China have middle class populations that far exceed the US, with even a small fraction of their populations having achieved 'middle class' status. While the United States graduates 70,000 engineers, India graduates 450,000 and China graduates 700,000 engineers. It is clear that such trends in global demographics will continue to progress as more and more 'under-developed' countries successfully enter the global marketplace.

China is regarded as the third most prolific space faring nation, as it has just recently completed its first successful space walk. While only the third country to have done a space walk, the Chinese space program has been involved in space related activities since the early 1950s (China's first spacecraft designed for human occupancy was the Shuguang-1 in January 1968.) ("Chinese Space Program," Wikipedia). China also has a growing population involved in biogenetic engineering education, with 32 programs teaching at the master's level and 9 teaching at the doctorate level. The Chinese government is actively supporting the growth of nanotechnology. China's major urban hubs such as Beijing, Shenyang, Shanghai, Hangzhou and Hong Kong, account for some 90 percent of all Chinese nanotech research and development (Nemets). With the accelerating pace of development in these countries, the United States will no longer hold a commanding lead in these areas without adopting a new way of working.

Changes in the "Green" Force

With the emergence of the global concern for the environment, "GREEN" efforts will continue to grow. With the monumental rise of environmental concerns, we, as a country, are realizing that we are destroying the planet, and soon all eyes and our collective consciousness will be turned in this direction – what will this mean for NASA's laboratories? NASA has already made contributions to our understanding of global green house gas emissions, global pollution, water supply purity and global agricultural activity. Consider the global complexity of these issues: it takes 232 KG of grain to make enough fuel to fill up one car's tank with ethanol, which is enough to feed a growing child for a year.

Other countries are fast approaching the Holy Grail of oil independence; Spain, for example can produce nearly 15 GWatts of wind generated electricity, and has produced enough to supply over 40 percent of the country's electricity needs. Several early wind turbine airfoil cross-sections were tested in NASA's Low Turbulence

Pressure Tunnel. It will take a concerted effort on the part of NASA's research establishment to take on these problems. The 21st century lab at NASA will be ideally suited to take on such challenges.

Innovations in Innovating

We are also experiencing significant innovation of the innovation process itself, leading to much shorter times between the development of new technologies and their appearance in engineered solutions. The 21st Century innovation process requires a new model for the relationship between the research and technology development process and the innovation process. The 21st Century Laboratory must be adept at cultivating such new relationships with innovators in order to remain relevant and viable. This change, as with all of these changes, is closely interwoven with the great increase in communication courtesy of the web.

According to Christopher Surridge, managing editor of the web-based journal Public Library of Science On-Line Edition, "The first generation of World Wide Web capabilities rapidly transformed retailing and information search. More recent attributes such as blogging, tagging and social networking, dubbed Web 2.0, have just as quickly expanded people's ability not just to consume online information but to publish it, edit it and collaborate about it—forcing such old-line institutions as journalism, marketing and even politicking to adopt whole new ways of thinking and operating" (qtd. in Waldrop).

The accelerating advances in science are being fuelled by the massive increase in information that is readily available to anyone, as well as the intense interactive communications among collaborators. Surridge further commented that "critiquing, suggesting, sharing ideas and data—this communication is the heart of science, the the most powerful tool ever invented for correcting mistakes, building on colleagues' work and creating new knowledge." Though Surridge believes classic peer-reviewed papers are important, he feels they are "effectively just snapshots of what the authors have done and thought at this moment in time. They are not collaborative beyond that, except for rudimentary mechanisms such as citations and letters to the editor" (qtd. in Waldrop).

What is at stake for us?

Langley research Center (LaRC) has between $2B and $4B Capital Replacement Value. The Agency's current replacement value is likely to between $25B to $50B. LaRC represents a very large annual investment in infrastructure, currently estimated between $50M to $100M. This represents between a $1B to $2B investment over the next 20 years. Similarly, the Agency's investment can be expected to be between $10B to $20B in upkeep over the next 20 years. From this, it is reasonable to infer that Centers have to think very carefully about any investment in labs and facilities. The cost of upkeep, never mind revitalization, of this enormous inventory is truly overwhelming.

To more fully explore the concept of the 21st Century Lab, we must focus more deeply into "the what" and "the how." These are the two fundamental keys to defining the future state. After being summarized below, these two keys will be examined in more detail in the remaining sections of the paper.

> **The what:** What problems require solutions that a 21st Century Laboratory enables? As a start we (at LaRC) have chosen several Grand Challenges to be the initial problem set, which can guide our thinking about the 21st Century Lab.
>
> **The how:** Leverage the anticipated dramatic developments in information technology (advances in tele-presence, information synthesis into knowledge, systems-level invention, managing complexity, emulating and accelerating cognitive processes, and integration of solutions into the 21st Century innovation economy). The essential capabilities include, but are not limited to: (a) applications of neuroscience to practical machine intelligence; (b) systems-level testing for validation; (c) bandwidth, in the form of widely distributed access by researchers to the knowledge base from anywhere in the world; and (d) information and knowledge depiction in the form of immersive, global, multi-sense inputs for use by researchers to achieve understanding of all dimensions of the problems of interest.

II. GRAND CHALLENGES

The initial problems to be solved by the 21st Century Laboratory are likely to be those problems that we now think of as "Grand Challenges." Grand Challenges can be thought of as high payoff, compelling opportunities that represent technical challenges that are beyond our current capabilities. We (at Langley) have developed a list of grand challenges, which can serve as a guide to the conceptual design of the 21st Century Laboratory. These grand challenges were chosen to be (a) beyond our current capability to solve; (b) relevant to the NASA mission, compelling and inspirational, and enabling revolutionary advancements in Mission affordability, safety or functionality; and (c) transformational in character, consistent with the technology revolution. Grand Challenges are expected to contribute to a healthy research environment by providing the context and motivation to pursue creative ideas and to stimulate innovation. Grand Challenges are also expected to provide guidance for future workforce critical skills and a mechanism for guiding facilities for the future. Finally, such Grand Challenges can contribute to the motivation, vision, technical scope, and advocacy for future programs in Science, Aeronautics, and Exploration.

In 2006, LaRC conducted an intensive 3-day workshop to develop a list of Grand Challenges that would serve as a guide to the conceptual design of the 21st Century Laboratory; the following Challenges were identified:

1. **Designer Extreme Materials**
   Tailor material systems to expand the design space for applications in extreme environments, such as space.

2. **Climate Understanding and Prediction**
   Explore the development of technologies to measure and monitor greenhouse gasses in the Earth's atmosphere, and to also explore low-carbon energy generation technologies.

3. **Characterization and Traversal of Planetary Atmospheres**
   Enable the exploration of planetary bodies that have atmospheres, which include "Earth-like" bodies with atmospheres and solid surfaces (which include Mars, Venus, Titan) and the giant planets with very deep atmospheres (such as Uranus and Neptune).

4. **Synergistic, Integrated Commercial Aircraft Design**
   To achieve simultaneously the goals of improved safety, lower community noise, reduced environmental impact, increased efficiency, improved security, and better affordability.

5. **Digital Airspace**

Consider developing new vehicle concepts and make them a practical reality. Also enable vehicles and other airspace users to share airspace safely.

6. **Advanced Cognitive Computing**
   Explore the idea of "Machines That Think," through the convergence of information technology, biotechnology, nanotechnology, and neuroscience. Also enable revolutionary missions through the application of machines that think.

7. **Earth to Orbit Spaceliner**
   Within a quarter of a century, enable transportation between Earth and Space that is routine, commonplace, safe and affordable for passengers, and economical for cargo delivery.

8. **Affordable Exploration**
   Increase our ability to get mass into Low Earth Orbit (LEO). Develop a practical LEO launch, lightweight exploration hardware and power systems, and effective in-space propulsion system using lightweight materials. Develop architectures using a 'systems' approach.

9. **Immersive Virtual Human Exploration**
   By 2025, enable human exploration of the solar system using virtual reality technologies to translate data received from advanced planetary robotic systems into 3-D immersive environments with '5 senses capability', focusing on visual and haptic senses.

III. THE 21ST CENTURY WORK ENVIRONMENT

A Creative Work Environment

The characteristics of a Future Lab State include broad and agile collaboration (which, as the norm, is international more often than national). We already have our intellectual capitol (which, at a minimum is required to "get in the game"). We also have the right set of computational, experimental and analytical tools, which provides the opportunity for ourselves and for others to contribute. The work environment is an essential element in stimulating creativity and innovation. As a governance philosophy, our researchers must be allowed time to think, with perhaps some percent (10-20 percent) unstructured, unencumbered time to pursue creative ideas.

Consider Best Buy's 'ROWE' or Results-Only Work Environment. "In a ROWE, each person is free to do whatever he or she wants, whenever they want, as long as the work gets done. Currently, there are two authentic ROWEs—Fortune 100 retailer Best Buy Co, Inc. and J. A. Counter & Associates, a small brokerage firm in New Richmond, WI. At both organizations, the old rules that govern a traditional work environment—core hours, "face time," pointless meetings, etc.—have been replaced by one rule: focus only on results." This environment has allowed a Fortune 100 company to "increase productivity at headquarters 41% while decreasing voluntary turnover as much as 90%" (Ferriss). In a research laboratory, such an environment would be characterized by:

- Masses of information taken in/digested [regarding BOTH the problem and potential solutions]
- Well-defined goals and an important challenge
- Tolerance for failure/management of risk [via multiple solution paths]
- Capitalize on failures
- Perserverance
- Independence/open environment/flexibility
- Multiple prospective solutions [adapt, combine, create, invent, collect]
- Absolute honesty, toleration of rebellion/argument/questioning
- Encouragement/rewards
- Adequate resources
- Minimum administrative overhead (protection, to the maximum extent possible, from programmatic and institutional exercises)
- Working with no walls, i.e., working across disciplines and across problem areas
- Autonomy at the lowest level
- Small workgroups

Changes in the Way We Do Work

Consider the differences in the way in which work is conducted in the typical workday; we work with friends and colleagues across the country (or across the world) every day. Many of us travel over 25,000 miles per year. Rising fuel costs are undoubtedly going to change this. In 2027, work will be conducted in ways we have not yet imagined, with a workforce model we do not understand today. Consider the workforce of the 21st Century Lab–Generation Next! Our children's generation will make up the Center Senior Leadership; our grandchildren will be their new hires. The generation NASA is hiring now: the thirty-somethings "Generation X" ("Generation X," Wikipedia) grew up during the end of the Cold War and the Ronald Reagan eras.

The economic recession of the 1990s and 2000s has resulted in a volatile employment history for Gen X; they have seen a decline in permanent job contracts, experienced outsourcing and off-shoring, and often experienced years of unemployment or underdeployment at typical jobs. Many individuals of this generation are overeducated and underemployed; many have a *take the money and run* work attitude ("Generation X," Answers.com). These folks will be **retiring** in 20 or 25 years! The workforce generation of the 21st Century Lab are described by Wikipedia as Generation Y, also known as the "World Wide Web Generation." Born since the explosion of the home computer market in the mid-to-late 1980s and 1990s, these folks will never have known anything else.

While it is very difficult to imagine the future with any precision, we can see some examples today, even in our own labs that foreshadow the future lab:

Examples Today

Gen-X Physicist is studying hypersonic combusting flows by developing advanced spectrographic methods (Coherent Anti Stokes Raman Scattering) in an "around the clock" collaboration with Australian and German Scientists. This activity is funded by all three nations, since each has an interest in the results.

Johns Hopkins University Hospital is now working on "Robo Sally," a robotic device that will be used to disarm bombs. Such a Robo Sally would be ideal to explore hostile environments of planetary surfaces ("Robo Sally Set for Battle").

Of course, at even small interplanetary distances (here to Mars), the fact that communication is limited by the speed of light makes communications to the Martian (and even the lunar) surface awkward. However, if communication were enabled at faster-than-light speed (FTL), this problem is eliminated. There has been some credible work recently reported in this area (Gibbs). To get a handle on Faster Than Light Communication, one should understand "Quantum Entanglement." In the world of quantum mechanics, the phenomenon of entanglement suggests that two "entangled" particles are so deeply linked that measuring one influences the other, regardless of the distance between them. In some interpretations, a signal passes between the two particles faster than light. To test this idea, Daniel Salart and colleagues at the University of

Geneva in Switzerland sent pairs of entangled photons to labs 18 kilometers apart. By measuring the properties of each photon in many of these pairs, the team showed that if superluminal signals are responsible for entanglement, they must travel at more than 10,000 times the speed of light (Salart et al.).

IV. EXPECTED STAGES OF DEVELOPMENT AND IMPLEMENTATION ISSUES

The Laboratory of the 21st Century will be nothing more than a node on a Network of learning and innovation. There are three fundamental questions that are part of defining the implementation path to the 21st Century Lab. These are:

1. When do we get to the point of knowing the physics in a particular discipline area well enough to not need experiments?
2. What do social trends mean? … As short-term social trends emerge, will we see knee-jerk reactions to rapid change (short-term reactions)?
3. Will long-term socialization be shaped by these forces and trends?

We expect the 21st Century Lab to evolve as follows (dates for each stage are approximations):

Stage 1 (now through 2020)
Human operators of physical experiments will remain on Center. Others can work from…wherever (it does not matter), performing technical piece work (where they are paid for output, we can then draw on all of the world's technical resources, where technical entrepreneurs are hired as problem solvers). To be successful, the Center must revamp its Procurement and Human Resource Management processes.

Stage 2 (2020 through 2035)
As we expect IT advances to be key to these advances, we see an increase in the focus on simulations, with dramatically fewer physical experiments; only tele-robotic physical experiments are conducted, going 24/7, if needed (as was done in BART during the 1990s). During this period, we will see the initial stages of invention by machine; we will also see dramatic energy savings due to increased reliance on information technology and telecommuting and decreased testing in large facilities. We can also expect plummeting costs, as typically follows with most technology revolutions (i.e., computers, telephones, etc.).

Stage 3 (beyond 2035)
The merging of biological and digital systems will produce enhanced human and machine performance. We will see machines that innovate, integrate, and can actually demonstrate wisdom. We will also see the convergence of human biology and machine capabilities, which will alter the concept of both entities (this will be the "cyborg" emergence).

V. IMPORTANT QUESTIONS WE NEED TO ASK OURSELVES

1. **Can we implement? What are the integration issues?**
   We can implement if we make a case built on meeting NASA mission needs with less cost, time, and more capability. However, integration becomes a central theme, as does social friction, hackers, and other dysfunctions.

2. **How do we make NASA LaRC's transformation to a 21st Century Lab happen?**
   First, we should stay abreast of the rapidly developing information technology, with a focus on the Advanced Cognitive Computing technical challenge. The key intellectual exercise is to identify what will be the long-term research challenges and the engineering tools of the future (20 years from now) and, by inference, what research and facility investments should be initiated now so that we will be strategically positioned to be relevant in the future. We should then begin to drive the revolution within the broad aerospace community. We could use the Advanced Cognitive Computing system, asking it to identify the right research and facility investments from first principles, rather than accept the status quo.

   We can consider a similar Advanced Cognitive Computing solution set for all lab maintenance, etc. We could build a case on competitive advantages accrued. We will need to reexamine our thoughts on New Town. For example, new offices may not be what we need 20 years from now. We could argue that offices house the arbiters of the NASA technology piece-workers. It will make sense to plan the obsolescence of the infrastructure we have now.

   An increase in telecommuting can have a profound impact on the Center. As employees perform job functions off-site on a more regular basis, maintenance requirements for facilities (labs and office buildings) will decrease. We should strategically revise our maintenance schedules to account for this decreased usage; in essence, we should, with some margin, adopt a policy of "Capital Obsolescence." For example, do we replace the current phone system, converting entirely to cell phones and put the savings into a 10GB/Sec Internet? As with any IT investments "the cost of doing it right is throwing everything away every two years."

3. **What are the barriers and what are the options (execution strategies) to overcome them?**
   We are entrenched in a 20th Century industrial model with respect to "Competencies." We could start an S-curve (see figure 1) to initiate a transition.

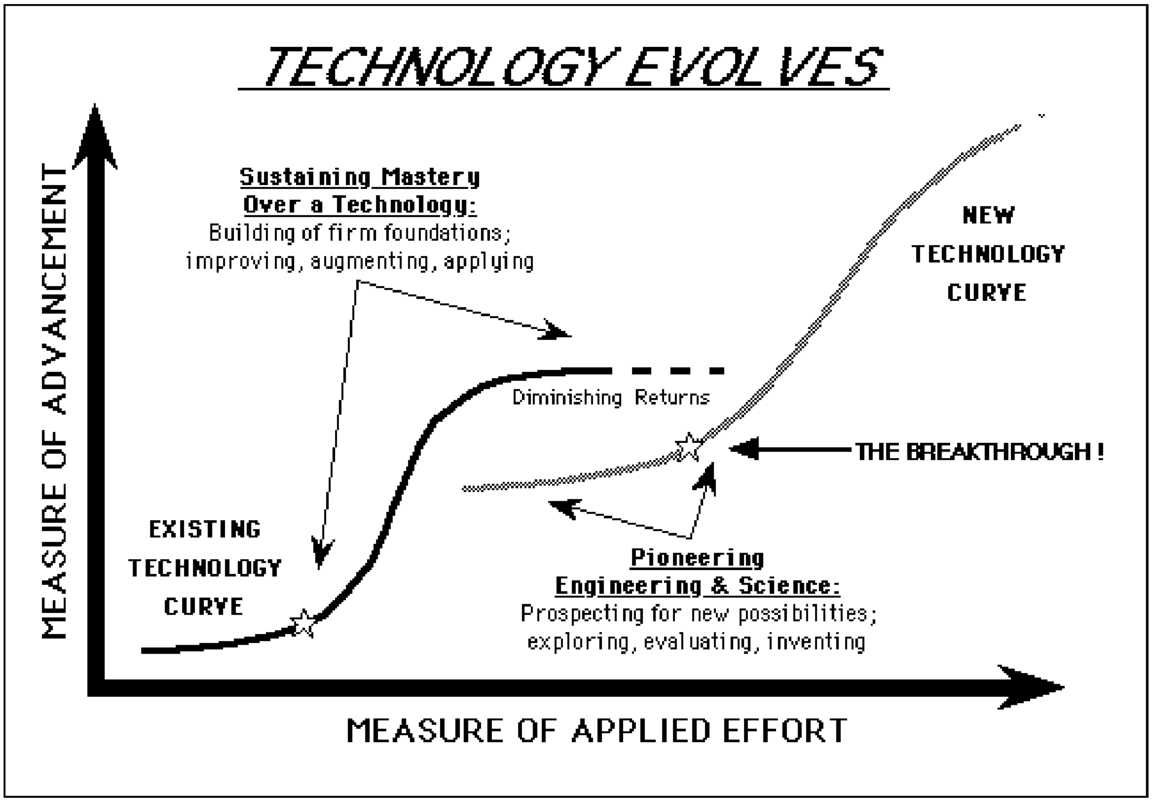

Figure 1. S-Curve diagram by Laird Close, University of Arizona)

We should at least be able to participate in the emergent phase of an S-curve. A significant barrier is self-inflicted social friction, or a resistance to anything technically new from those that are opposed to technological progress or technological change (affectionately called "Luddites" after a nineteenth century movement that opposed the introduction of looms that could be operated by cheap, relatively unskilled labor") ("Luddite," Wikipedia).

Another source of resistance is our own mental models for the organization of work. As these 21st Century Lab ideas are different from what we are used to, work is organized fundamentally differently than it used to be. Workers no longer put in the time, but rather, they are paid for accomplishing a specific task with an associated product. Adding social and political influences will further retard the 21st Century Lab development timeline, especially in a government laboratory, where whole institutions are in place to protect traditional work models.

It can also be stated that secondary effects will be hard to anticipate. It is hard to anticipate "non-linear" effects (effects on effects, including unintended consequences). It will also be a huge step to get leadership to embrace international value. There are those that believe that NASA's technological prowess is not developing at the leading edge of technical change, NASA is deeply rooted in the past, putting NASA's relevance at risk over the long term.

As we create value networks for problem solving, a **Global Intellect** emerges! In the new world of Internet, etc. what one person knows, we can all know (we just need to Google™ it!). In the 21st Century Lab, the NASA organization will serve as a host for solution seekers, where a well-connected employee of NASA will have a network of other clients.

Unfortunately, competencies are not embedded in organizations, but there may be an organization that is charged with advancing, say, climate science for the United States; in the future, we will be buying networked solutions. The key to innovation is to create, borrow, or adopt thousands of inventions, link them, filter them, etc., for solutions useful to the Agency. This is the effect of being networked. The goal of the Center is to become a well-connected percolating cluster that effectively develops, manages, and grows innovation processes that will solve problems of national importance.

4. **What will connect the 1-5 year efforts and the 20 year horizon?**
   Connecting the very near term efforts with the lab's 20 year horizon is a real challenge. We may need to think about possibly re-crafting the next phase of New Town, or experimenting with new ways of organizing work. For example, we could develop (long distance) telecommuting as an organizational strategy. We could create an InnoCentive ("InnoCentive," Wikipedia) project (or two), or we could develop a 24/7 global robotic experiment, all of which present significant Human Resource Management, Procurement and Legal challenges; support from these organizations would be essential to the success of these strategies.

5. **What assumptions are we making that are limiting our thinking?**
   Clinging to the linear view will limit us. Many believe that NASA programs are too narrowly focused on meeting short-term goals and, as a result, that we tend to be risk averse. We will be limited if we dismiss social and political effects. We have the mind-set of constrained resources, managing scarcity (for example, with respect to oil, the environment, or space launch).

6. **What external reactions might we anticipate?**
   We will encounter the problems of all first-time innovators: we have to create the market. Our perceptions on telecommuting could have adverse reactions. We have not organized this effort for benefit of the Agency (so we can close an entire (old) building or develop an innovative space transportation system). The 21st Century Lab requires a far more advanced mental model–it requires an explicit plan for change. John Kotter, a Professor of Leadership at the Harvard Business School, developed a model for leading change. He has identified a three-step process to achieve successful change, including "defrost the status quo, take actions that bring about change, and anchor the changes in the corporate culture" (qtd. in Rose). If we're not tracking to this double exponential, we're dying. We can count on machine intelligence arising. There are pedestrian off-ramps at every turn (for example, we could choose to cling to the old infrastructure, etc.)

The other cross-cutting approach is to create a foundation from which the 21st Century Laboratory can emerge. NOTE: These exponential curves are immutable, we can choose to ride these waves or just watch them go by! Those organizations that don't engage will die, (even some of those that do may die)! The key is to be agile enough to be on the curve.

7. **Where does the money come from?**
   Reframing the question in the context of 21st Century Lab: How do revenue goals shape our plans? This question should drive our desire to be a well-connected percolating cluster that effectively develops, manages, and grows innovation processes that will solve problems of national importance to the commercial aviation industry.

8. **What steps need to happen right now?**
   We need to create an outcome-oriented Center (the Exploration program helps with an outcome-oriented mentality, and it engages us in the realities of delivering critical path hardware. We must, however, remember to keep 20 percent of our workforce doing superb innovative work (which is somewhat akin to developing our workforce to be schizophrenic).

VI. CONCLUDING REMARKS

As described in this White Paper, the concept of the 21st Century Laboratory is not a proposal for a new program or project– it is, rather, an environment, both physically and virtually, where key technologies are further advanced, validated, and applied to problems of significance to the Agency. The 21st Century Laboratory encompasses not only the infrastructure and facilities, but also the workforce and practices that will be required to meet the needs of the future laboratory environment. Far greater reliance on networking and collaboration will need to be realized. The past five decades have brought significant technology advances and, due to the accelerating pace of technology change, we expect the next two decades to bring even more advances, which we will apply and leverage to meet the Agency's long-term technical challenges.

A number of elements are present that will certainly change how we do work in the future. First, the advancements in computational tools, speed, and cost have resulted in a rapid maturation of our physics-based design tools over the past 20 years. The expected continued advances will play a key role in solving complex problems. Advancements in physics and physics-based models will also play a key role in the 21st Century Lab. As our understanding of physics improves, we will be able to design tools based on these advances, thus improving our modeling capabilities. Innovation will continue to be critical to the success of the 21st Century Lab. The technology innovations that are common today (i.e., world wide web, blogging, social networking, etc.) are allowing individuals to access more information than ever before, and allowing them to share this information with a much wider audience in much less time. The 21st Century Lab will leverage this increased communication capability, with the hope of reducing the time it takes to get an idea from concept to application.

The ability for Langley Research Center to leverage technological and physical advances will have a large impact on our ability to remain a viable Agency asset. With the cost of maintenance and revitalization continuing to grow, we must make intelligent investments in our laboratories and facilities. In order to do so, we must understand the problems that will require solutions, be able to leverage the anticipated developments in information technology, and be aware of essential capabilities that will be needed.

In an effort to meet future technical challenges, we have developed a set of Grand Challenges, which we consider to be high-payoff, compelling opportunities that represent technical challenges that are beyond our current capabilities. The challenges will provide conceptual guideposts as we move towards the 21st Century Lab. We feel these challenges will contribute to a healthy research environment, provide guidance for determining future critical workforce skills and facility investments, and serve to help us more effectively advocate for future programs.

The work environment of the 21st Century Laboratory will be one that fosters creativity. In order to achieve such an environment, increased collaboration will be essential, as will a change in how workforce is assigned to programs and projects. We highlighted the concept of a Results-Only Work Environment, which gives employees more freedom in how they spend their time, as long as the work is accomplished. This concept is far from our traditional approach. In order to adapt to a more flexible work environment, we must also change our mindset when it comes to such things as face-to-face meetings. If our collaboration with external partners increases, we will need to develop alternate strategies to get our work accomplished more efficiently, while spending less. The workforce of the 21st Century Lab will have a much stronger reliance on information technology, both in the form of methods for communication and advanced hardware and techniques.

In order to reach our expected end state for the 21st Century Lab, we have identified a number of expected stages of development, as well as implementation issues that will need to be addressed as we progress. It will be critical that we understand and resolve issues during each step, so that we can make necessary adjustments as early in the process as possible, including alternate technology investments, skill mix, etc. We must be willing to explore new ways of doing business, including alternate work schedules, expanded collaboration, and allowing workforce to pursue leading-edge technical research. While we realize the transition to the expected end state may not be easy, Center leadership is committed to providing the tools and resources to make it a reality.

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14. ABSTRACT
The name “21st Century Laboratory” is an emerging concept of how NASA (and the world) will conduct research in the very near future. Our approach is to carefully plan for significant technological changes in products, organization, and society. The NASA mission can be the beneficiary of these changes, provided the Agency prepares for the role of 21st Century laboratories in research and technology development and its deployment in this new age. It has been clear for some time now that the technology revolutions, technology “mega-trends” that we are in the midst of now, all have a common element centered around advanced computational modeling of small scale physics. Whether it is nano technology, bio technology or advanced computational technology, all of these megatrends are converging on science at the very small scale where it is profoundly important to consider the quantum effects at play with physics at that scale. Whether it is the bio-technology creation of “nanites” designed to mimic our immune system or the creation of nanoscale infotechnology devices, allowing an order of magnitude increase in computational capability, all involve quantum physics that serves as the heart of these revolutionary changes.

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