Building NASA's Future

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Let me begin by thanking Dean of Engineering Nick Jones for inviting me to speak this afternoon. My prepared remarks will be mercifully brief, so that we can have more time for an interactive dialogue. I think that is the way that Fred Billig would have liked his namesake lecture to be conducted. I hope his daughter Linda Baumler, who is here with us today, would agree.

Fred was an accomplished researcher, a superb engineer, and a masterful teacher who knew how to capture the imagination of both his students and his younger colleagues. Early in my career, it was my great good fortune to know and work with him as a teacher, mentor, and supervisor. He knew that teaching and mentoring young engineers paid long-term dividends as the torch passes from one generation to the next.

As I prepared for this lecture, thinking about Fred and his role in my life caused me to reflect upon the different means by which we engineers go about learning and applying our craft, about how we acquire the skills we need to practice our profession.

We certainly live in a different world than the one in which I was schooled. Where once there were only books and professional journals to capture knowledge, today we are surrounded by the ubiquitous tools of modern communication and information dissemination. The internet, with web pages devoted to any subject imaginable, and many that I, personally, would never have imagined. News and entertainment available 24/7 via world-wide cable TV. Cell phones and PDAs. Virtually constant connectivity. Email. Instant messaging. Texting. If you are an engineering student today at any level, you grew up and are at ease with a host of things that my generation didn't have. But lest you think that I am an old guy reminiscing fondly about the past, let me remind you that my generation isn't ignoring these things; in fact, we invented them. … You're welcome. … But I think most of us will admit that you're a step or two ahead of us when it comes to applying them in daily life.

But I do still think that a personal, one-on-one connection, a teacher-student, master-apprentice relationship such as I had with Fred, conveys a richer understanding of the art and science of engineering than does a lecture, a paper, or even an interactive website. Much of what matters most about our tradecraft simply cannot be learned from books, coursework, and online sources, it must be passed from mentor to novice. There is a rich lore of engineering practice that is unwritten, and can't be written, but which passes down from veteran to trainee.

Finally, of course, there is the knowledge that is gained by direct experience. Even this early in your careers, you are probably aware that such knowledge is nearly always very hard-won. Indeed, the greatest value of mentor relationships is that they allow some of us, some of the time, to learn from the experience of others.

This brings me to the key point of my lecture today, which I hope you will find to be valuable in your future. By all means, study the academic, formal methods of engineering, science, and mathematics as much as you possibly can. The effort of doing so is never wasted.

Learn as much as you can of the history of engineering. Learn especially from the famous failures and the lessons they can teach, which are always so much more valuable those derived from success.

Listen closely to what we pilots call "hangar flying", the talk of veterans who have survived to become such. The lore of engineering practice that passes down from experienced practitioners by word of mouth is priceless.

But, most of all, *live* the experience of engineering. Don't specialize too soon. Build your career, especially your early career, around the goal of gaining the most relevant and varied experience you can obtain. Make your career moves with this goal in mind. Don't just study engineering. Live the experience of it. It doesn’t happen like the books, the histories, even the tales of our veterans, would have you believe.

Caldwell Johnson, Max Faget’s partner in the development of the Mercury, Gemini, and Apollo spacecraft designs of the 1950s and ‘60s, once offered an insightful comment about how and why engineers so often fail to explain what really happened as they tell the story of their work. He said, “The way the history books say things came about, they didn’t come about that way. The official records and all, that’s a long way of explaining a lot of things. It turns out that the thing was done by people, not by machines, and people have a way of coming to a very rational conclusion in a very irrational manner.”

Caldwell was talking about the elusive, non-rational qualities of engineering judgment, creativity, insight, and intuition, the ability to see a design or a process not as a set of interconnected pieces, but as a thing in the whole. This is an attribute for which we don’t have precisely the right word in English, but the meaning I’m looking for is captured perfectly by the German word *gestalt*.

We all have this intuitive ability, though of course we do not all have it to the same degree. In my field, aerospace engineering, Max Faget and Caldwell Johnson are revered even today, decades after their greatest accomplishments, because individually and as a team the solutions they produced to the problems they encountered simply oozed this creative intuition.

An excellent discussion of the role of intuitive judgment in human cognition and action – for both good and ill – is offered by Malcolm Gladwell in his book, *Blink!* If you have not read it, I would urge you to do so. It will, and should, color your view of how to apply your training and education to develop the intuition you will bring to the problems you encounter in your career.

Perhaps one of the reasons why we as engineers don't like discussing the messiness of such irrational behavior is that it is in our genetic makeup to fix it! We like order and predictability, natural law and the logic of mathematics. We like to believe that the act of creating something new from the whole cloth, something that has never before existed in the history of the universe, should and can follow a natural, obvious, and orderly process.

But in reality, life and the decisions we make every day are not so well-ordered and rational. We must make decisions with less information than any rational person would prefer to have. Yet they must be made. To do this, we augment our formal training with experience. As the years go by, we learn what is important and what is not. We learn not more answers, but more questions. We learn that the purpose of education is to inform our intuition. We learn to live the experience of engineering.

Let me tell you a story about a great engineering team and a magnificent engineering accomplishment that might help put my comments in perspective.

The success of the Apollo missions to the moon is an achievement against which, for a very long time to come, all future engineering endeavors will be measured. We in NASA today are re-learning many of the hard truths about difficult problems that the Apollo engineers solved with slide rules or computers having far less processing power than the Blackberry in my pocket. But I find in talking with people that, looking back, the mists of time and the hagiography of Apollo have clouded our collective memory of the problems and doubts and adversity which had to be overcome on the way to the moon. Looking back across forty years, somehow the historic achievement of Apollo is seen today as having been compellingly inevitable. It wasn't. So, let me take you back forty years, to the spring of 1968.

It was a tumultuous time for our nation, with the Vietnam War, the assassinations of Martin Luther King and Robert Kennedy, the struggle for civil rights and women's rights, protests on college campuses, and a hugely divisive Presidential campaign. The baby boom generation – my generation – was coming of age. I was a sophomore here at Johns Hopkins, working on my golf game while masquerading as a physics major. And NASA was fifteen months away from carrying out the greatest engineering feat in history.

But back in the spring of 1968, it was far from obvious that we were so close, as President Kennedy put it in his May 25th, 1961 speech, "… to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to the Earth". The Apollo 1 fire which killed Gus Grissom, Ed White, and Roger Chaffee in January, 1967, NASA's darkest hour to that point, was still fresh in memory. In its aftermath, some Washington policymakers called for an end to the program. Thankfully, wiser heads understood that reaching for the unknown requires the fortitude to deal with adversity. Kennedy had understood that too, warning the Congress and the nation in his 1961 speech that, "If we are to go only halfway, or reduce our sights in the face of difficulty, in my judgment it would be better not to go at all."

Most importantly, NASA engineers felt themselves to be personally responsible for the tragedy, and committed themselves to fixing what were now seen as deficiencies in the Apollo command module design. A sweeping redesign was undertaken. The cabin atmosphere, the hatch design, the cockpit wiring, and the crew cabin materials were changed to eliminate ignition sources, to prevent the spread of any fire which might occur, and to allow immediate egress if necessary. NASA and contractor engineers raised their standards of workmanship, now fully appreciating the fact that lives depended on meeting the most exacting standards. They had lived the experience of failing to meet those standards, and refused to let it happen again.

But in April 1968 another major setback occurred, again calling into question whether the Agency could achieve the goal with which President Kennedy had so eloquently challenged the nation.

On the same day that Martin Luther King was assassinated in Memphis, NASA launched the Apollo 6 mission from Cape Canaveral. This would be the final unmanned qualification test flight of the Saturn V rocket and the Apollo spacecraft, the last test flight before risking astronauts' lives on a new vehicle.

In plain engineering terms, this launch was a failure. The Saturn V experienced severe "pogo" oscillations, longitudinal vibrations of the rocket, caused by uneven combustion in the F-1 first stage engines occurring close to the resonant frequency of the rocket vehicle structure. The vibration would have forced a crew abort from the Saturn V, never an attractive proposition. But that was almost the least of it; the pogo oscillations caused a second major failure, the rupture of a hydrogen fuel line in the second stage of the Saturn V. Two of the five J-2 second stage engines failed to ignite, resulting in a major loss of mission flight performance. The third stage limped into Earth orbit with its Apollo spacecraft payload, but with all fuel depleted. It had been planned to re-start the third stage, fly the spacecraft to high altitude, and then bring the spacecraft back to Earth on a high-speed reentry trajectory, simulating return from the Moon. That plan had to be scrapped.

At this point, I would like to digress for a moment. Some of you may have noted that the subjects of engineering, engineers, and their creations are not exactly a mainstay of the critically reviewed literature. Our profession is rich in textbooks and short on captivating tales about living the experience of engineering. But some have been written, and a few offer compelling narratives and insights into the minds, the lives, and the work of those who have created the world around us. Two that come to mind are *The Soul of a New Machine*, by Tracy Kidder, and *The Path Between the Seas*, by David McCullough. The first deals with the creation of a new computer in the nascent minicomputer industry of the early 1970s, and the latter with the four-decade history of efforts to build the Panama Canal. You will love them.

I know of two books about the early American space program that tell similarly compelling tales. The first is *Carrying the Fire*, by Michael Collins, who was the Command Module Pilot on Apollo 11, the first lunar landing mission. Mike is an engineer, test pilot, and astronaut who can put you in the cockpit beside him with his writing. But it was Charles Murray and his wife, Catherine Bly Cox, who co-authored the best book I have yet read about the space program. In *Apollo: The Race to the Moon*, they captured the experiences of the managers, engineers and flight controllers with a degree of insight that I have rarely seen anywhere.

In their book, they vividly describe the failed Apollo 6 mission. One of the better descriptions came from one of my best friends, legendary NASA flight director Jay Greene, who was a newly-minted flight controller at the time. When asked what he was doing in the control room as the Saturn V "wandered…as if a drunk had been drawing the trajectory" he said, "I was puckering." Needless to say, engineers worth their salt who, like Jay, go where the action is, will experience some moments like this in the course of their work. Some of you in this room may have experienced such moments. That is living the experience of engineering.

As engineers, we try very hard to learn from our mistakes. This is why we conduct flight tests and take the time necessary to analyze the problems revealed by those tests. In the process, we determine under real-world conditions whether or not what we *thought* should happen bears any resemblance to what *does* happen. If not, if we encounter unknown unknowns, or problems in integrating separate subsystems, or ensuring we have maintained the most exacting standards in building our machines, then we can effect fixes before proceeding. That's what good engineers do.

And that is what the Apollo engineers did. In the months following Apollo 6, the Saturn V thrust oscillation problem yielded to the more than one hundred engineers and four hundred technicians working on it. They realized that the natural frequency of the F-1 thrust chambers was too close to that of the vehicle as a whole, and various "shock absorbers" were added to the Saturn V.

While this was being done, the program moved forward. NASA flew the first manned Apollo mission on the smaller Saturn I in October 1968, and then launched the inspiring Apollo 8 mission around the Moon before Christmas, on only the third flight of a Saturn V, with the prior one having been a failure. The Apollo 8 crew was named *Time* Magazine's Men of the Year, and seven months later, Neil Armstrong and Buzz Aldrin touched down on the moon. In thirty months, the Apollo engineers had brought forth historic, epochal success from the wreckage of a launch pad fire and a failed flight test.

And now a postscript on the Apollo 6 flight itself. As I noted earlier, the third stage of the Saturn V was unable to boost the Apollo spacecraft to high altitude for its planned reentry system test. So, on the fly (if you will), the mission control team reprogrammed the Apollo computer to perform a lesser maneuver with the spacecraft engine, but one which still sent the spacecraft into an orbit with a peak altitude of several thousand miles. From there, they restarted the engine and drove the spacecraft down into the atmosphere at a speed nearly equal to that required for return from the moon. This test adequately met all of the originally planned guidance, navigation, and reentry flight test objectives for the Apollo spacecraft, clearing it to go to the moon. This in-the-moment rescue of what really ought to have been a complete failure – and NASA engineers have performed many similar feats over the years – has always seemed more impressive to me than some of our less exciting successes.

When NASA performs such feats – moon landings, operating rovers on Mars today, constructing the International Space Station, repairing the Hubble Space Telescope – we forget the hard work and sleepless nights of thousands of engineers, scientists, and technicians that goes into making it look easy. Since those engineers, scientists, and technicians are not getting rich from this work, I can only chalk up such selflessness to an innate desire to be part of something greater than themselves, to be part of making history. This is one of the real reasons why I love being part of the space business.

That is the spirit I hope you still find within NASA and in the conduct of our missions. The lessons of Apollo speak to us today, forty years later.

We are now in the process of designing and developing new spacecraft and rockets to replace the aging Space Shuttle, an endeavor which occurs once in a generation. And sometimes it is really true that the more things change, the more they remain the same. You might have noticed the recent media interest about potential thrust oscillation problems in the Ares I crew launch vehicle. These are not unlike those that plagued the Saturn V forty years ago. The oscillations of present concern are common to all solid rocket motors, but our initial analysis showed dynamic accelerations on the order of ±5 g, so it got our attention.

Since last November, we have had an engineering team looking into the risks of the Ares I thrust oscillation to identify the specific causes and find ways to mitigate them. The design team first conducted more careful analysis of the potential thrust oscillations. They determined that the first longitudinal mode would not be an issue, leaving only second-mode effects and a reduction of approximately a factor of two from initial predictions. They then developed some fairly straightforward modifications to the first stage to counteract the remaining problem. The most attractive of these is to use the parachute recovery system as a tuned mass damper – a shock absorber. As the launch vehicle design matures, we will also assess the effect of composite materials, field joints, and other features of the vehicle design to dampen the oscillations.

Needless to say, there’s always a certain amount of vibration when riding a rocket into space, so the Orion will design seats, displays, etc. to assure adequate crew performance. And if we need to take additional measures, we can detune the integrated launch stack by isolating the Orion crew vehicle from the Ares I launch vehicle to decouple the crew vehicle from the natural frequency of the overall launch vehicle stack. So, based on the work we have done, I think we have this problem well under control.

But you never know what it is that you don’t know, so we are still mindful of this and other risks. We’re maintaining a conservative engineering approach, gathering further data on Space Shuttle flights starting this fall, and on the initial Ares I flight test next year.

No one ever said that building a new space system would be easy. Again, John Kennedy's challenge to NASA and our nation speaks to us today: "We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win."

Two weeks ago, I was testifying at a hearing before the Senate committee that provides NASA's funding, and I tried my best to explain the worth of America's investment in NASA. While NASA's budget is 0.6 percent of the $3.1 trillion annual budget for the U.S. government (rounding error, in engineering practice), this small investment not only keeps us on the New Frontier of which Kennedy spoke so eloquently, it also benefits our nation by spurring development in new, innovative technologies and advancing our scientific understanding of the Earth, sun, solar system and the rest of the universe in ways we can hardly fathom today, but which inspire us to learn more. Space exploration also contributes to our national security in a very deep way, by enabling us to build closer ties with other nations and societies, and by inspiring young people like you to study difficult subjects – math, science, and engineering – so that the next generation of

Americans remains on the cutting edge of technical progress. I mean, after all, this *is* rocket science.

This is a challenge so great that it will not be finished in a single year, a single Presidential Administration or session of Congress, or even in the lifetime of anyone here today. It is a challenge for generations to come, including and especially your generation, but one which requires leadership on our part today on your behalf.

When I was in my early twenties, maybe about your age, the Apollo program was in full swing. Many of you were not even born when Apollo flew to the Moon, and I realize that for some of you, these achievements are ancient history. However, I am asking you today to embrace this history, both great and terrible, because there are powerful lessons still to be gained to guide and inform your careers. While I recommend that you live the experience of being an engineer, remain always open to learning from our past.

Many of you were not born even in 1986, when Space Shuttle *Challenger* exploded soon after launch, exploding with it the myth of NASA's invincibility. You do not and cannot know what that meant for our nation. But I hope everyone here remembers where you were five years ago when Space Shuttle *Columbia* disintegrated over the skies of Texas and Louisiana. It was a galvanizing moment for all of us in the space business, a moment which I hope and believe changed the course of space policy for a generation. Your generation.

Just as I described to you what happened forty years ago with the Saturn V on the Apollo 6 mission, I recommend that every engineering student read at least Volume 1 of the Columbia Accident Investigation Board report. It lays out some of those hard lessons of engineering, and some which transcend engineering. When you read it, I would ask you to remember Caldwell Johnson's comment about how people have a way of coming to very rational conclusions in a very irrational manner. Well, as Malcolm Gladwell shows us in *Blink!*, sometimes those conclusions are wrong. So, as engineers we need to take the time to reflect on the mistakes and failures in our profession, as well as the successes, and learn to apply those lessons to the new challenges before us.

My speech today is entitled "Building NASA's Future". I'm not talking about building new machines, though those will certainly be necessary. I'm talking about how we learn to be better engineers and managers. People are what will build a better NASA, because we are only as good as the know-how, creativity, and credibility of our people. We're all volunteers here, so I hope you will join us, and live this experience. I hope that you here will want to be a part of turning new designs into reality, opening the International Space Station to commercial space ventures, returning America to the Moon, and exploring Mars and worlds beyond. This will be the greatest engineering challenge of our time and for the next generation, and I hope you want to be a part of it. I certainly do.

That is the legacy which mentors like Fred Billig imparted to me, and I hope that I have in some small way imparted to you.

Thank you.