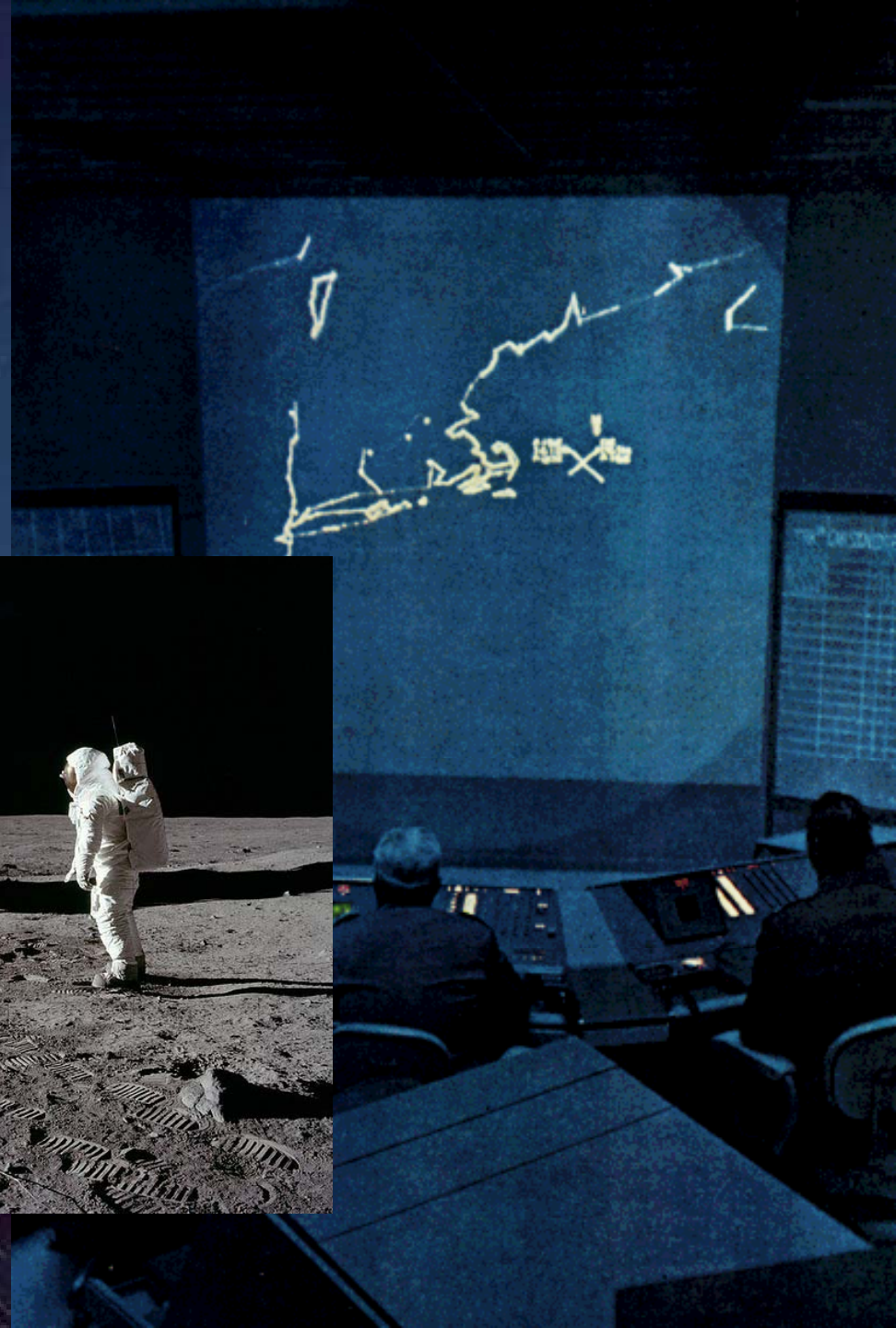
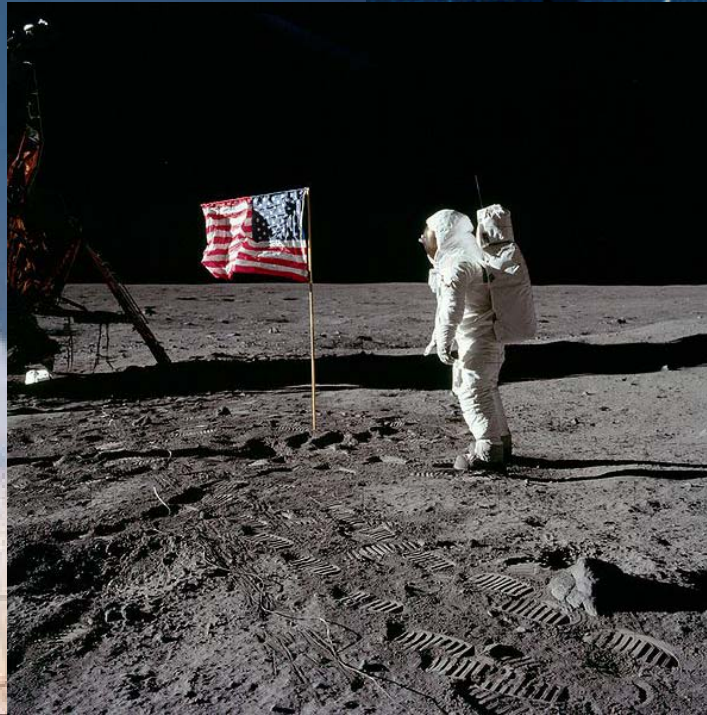


# The Origins of, and Reasons for, Systems Engineering

V. Arrichiello





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# The Origins of, and Reasons for, Systems Engineering

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Vincenzo Arrichiello, SELEX-SI Academy

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Systems Symposium IBM  
Rome, 29/11/2012

# Systems Engineering

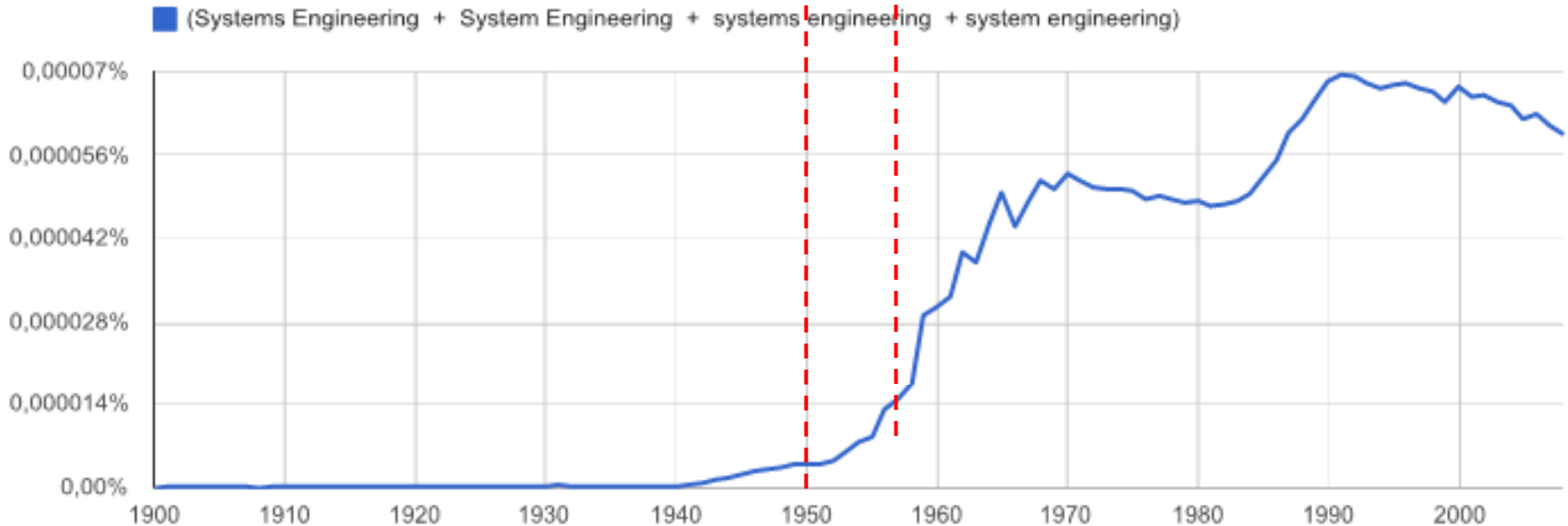
WHEN?  
WHY?  
WHO?  
WHERE?  
WHAT?  
HOW?

# When?

## Emergence of "Systems Engineering"

1950 G.W. Gilman (Director of Systems Engineering at Bell Labs) - Systems Engineering course at MIT

1957 - H. Goode, and R. Machol - System Engineering: An Introduction to the Design of Large-scale Systems



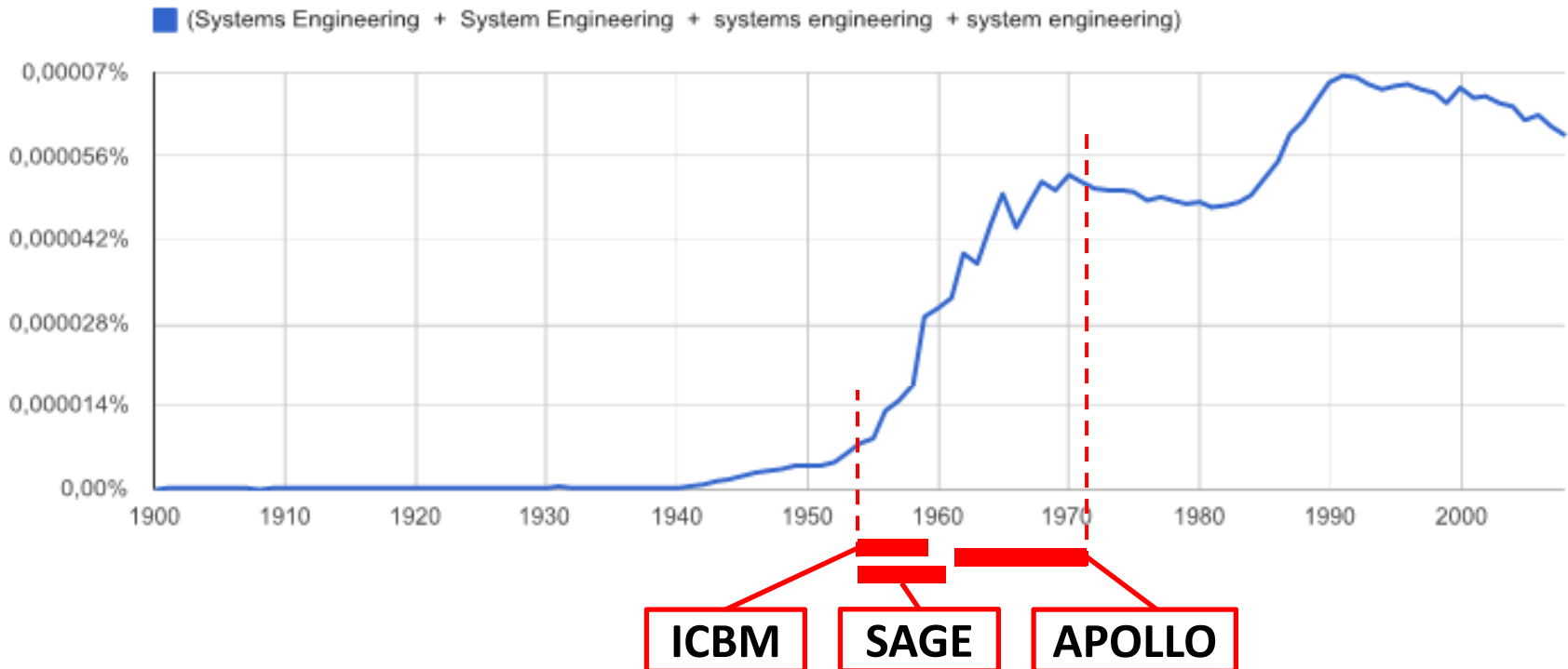
## Concurrence of large, complex programs

- Intercontinental Ballistic Missile (**ICBM**) development program (1954 - 1958)
- Semi-Automatic Ground Environment (**SAGE**) Air Defense System development program (1954 - 1961)
- **APOLLO** Advanced Manned Space Flight Program (1961 - 1972)



# When?

Systems Engineering was mainly developed  
*"out of necessity"* by these programs



# When?

## Historical Context

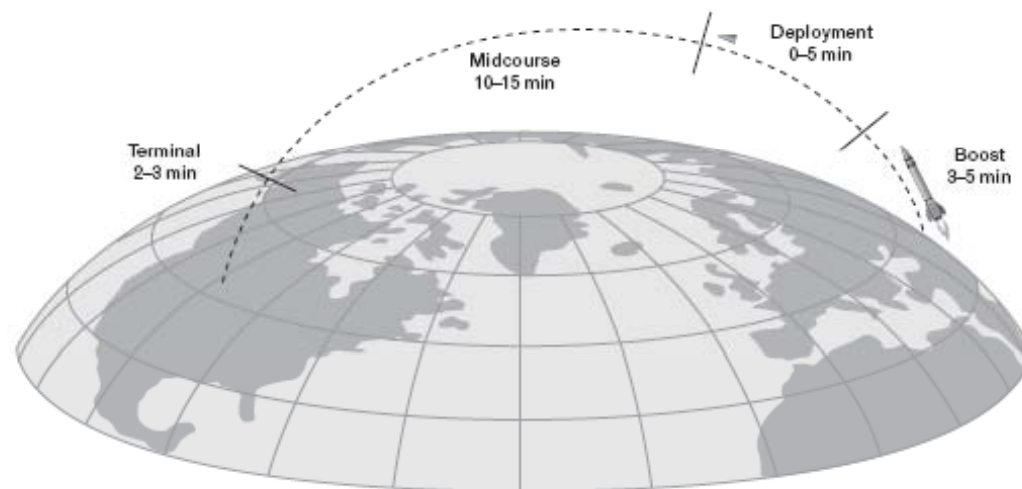
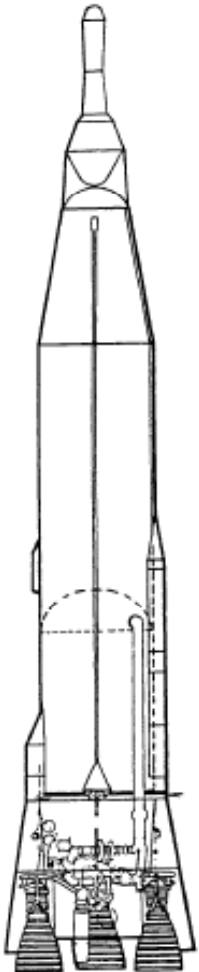


"On Guard! The Story of SAGE",  
IBM Corporation, Military Products Division, (ca. 1956),  
The Internet Archive, Prelinger Archives

## Intercontinental Ballistic Missile Program (ICBM)

The Air Force ballistic missile program is the **largest single military program ever undertaken by the United States**. It is managed by the Air Force, with the support of more than 30 major contractors, 200 major subcontractors, and 200,000 suppliers in industries across the Nation, whose joint resources include skills of thousands of scientists, engineers, and technicians.

Findings Resulting From Initial Review of The Ballistic Missile Programs of the Department of the Air Force - The Comptroller General of the United States, 1960





# Why?

## A Dangerous Mix



**Novel,  
heterogeneous  
technologies**

**Cold War  
technological  
race**

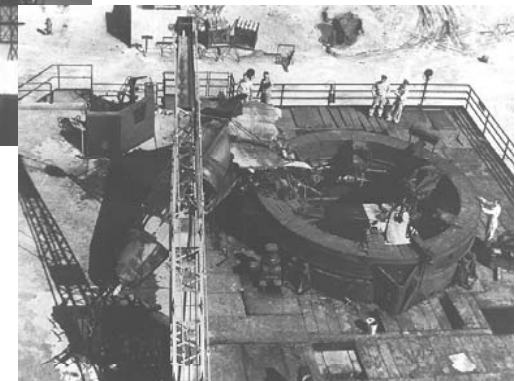
**Complexity**

**Failure rate**

**Compressed  
Time -scale**

## "Failure rates of early missiles ranged from 40 to 60 percent"

The United States Air Force and the Culture of Innovation, 1945–1965 - Stephen B. Johnson



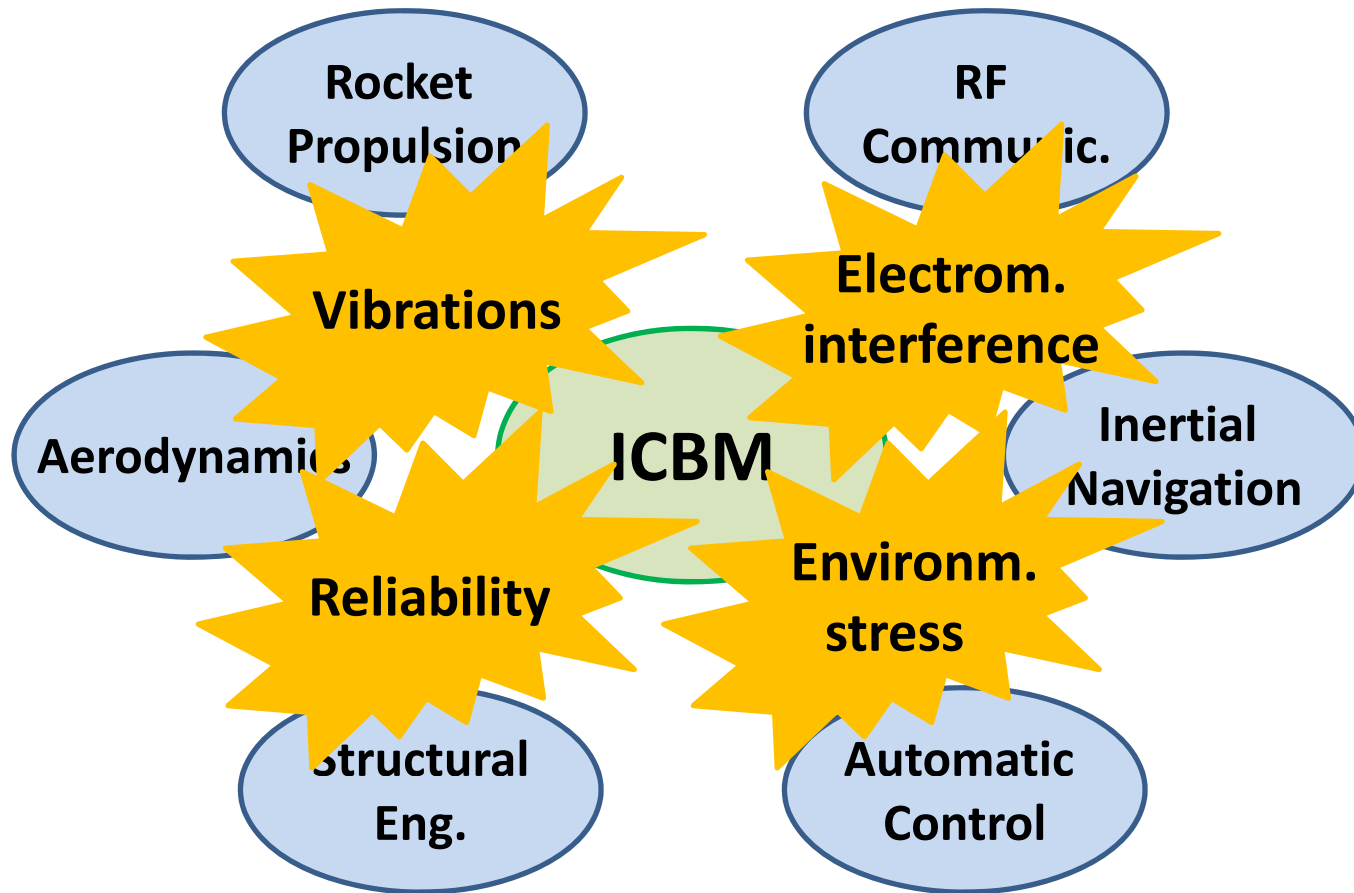
<http://www.fas.org/spp/military/program/6555th/6555c3-4.htm>

- Thor 101...reached an apogee of 6 inches whereupon...slid backwards...and **exploded**...
- Thor 102 **flight lasted 35 seconds**...
- Thor 103...**exploded** on the pad...
- Thor 104...**broke up** after 92 seconds...

[http://en.wikipedia.org/wiki/PGM-17\\_Thor](http://en.wikipedia.org/wiki/PGM-17_Thor)

# Why?

## Multiple Technologies *ADVERSE INTERACTIONS*



# Why?

## Multiple Technologies ***POOR COMMUNICATIONS***

**Rocket  
Propulsion**

**RF  
Communic.**

**Aerodynamic**

**Inertial  
Navigation**



Pieter Bruegel de Oude, De toren van Babel

**Structural  
Eng.**

**Automatic  
Control**

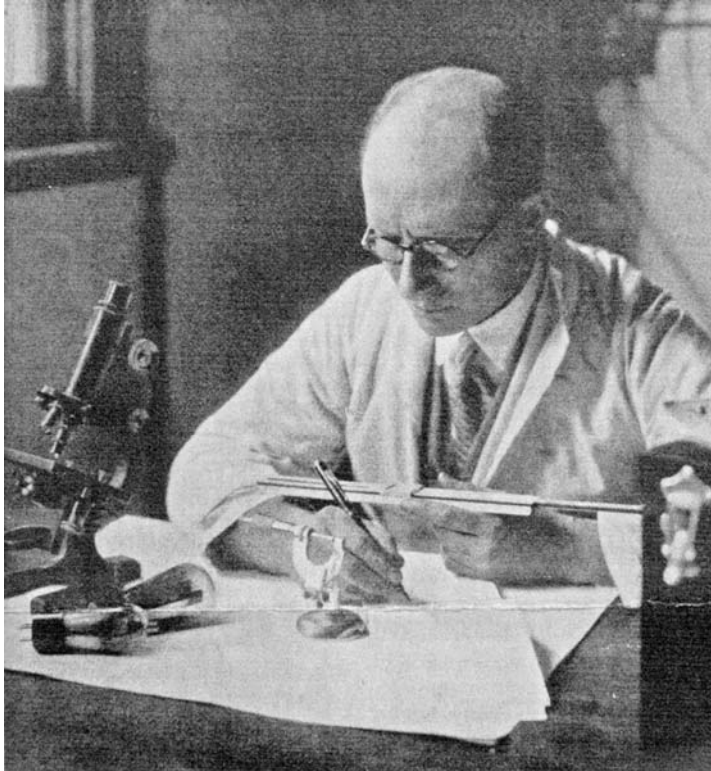
# Why?

## Diverse worlds





## Diverse *engineering* worlds



Joseph Griffith Reed  
Radio Pioneer



Robert H. Goddard  
Rocketry Pioneer

# Why?

The chairman of North American Aviation used to say:  
***"electronics is where you buy boxes that you connect together so that some things that don't work are connected to other things that also don't work. That's the definition of electronics."***

SIMON RAMO: An Interview Conducted by Frederik Nebeker, Center for the History of Electrical Engineering, 1995  
IEEE Global History Network, Oral Histories

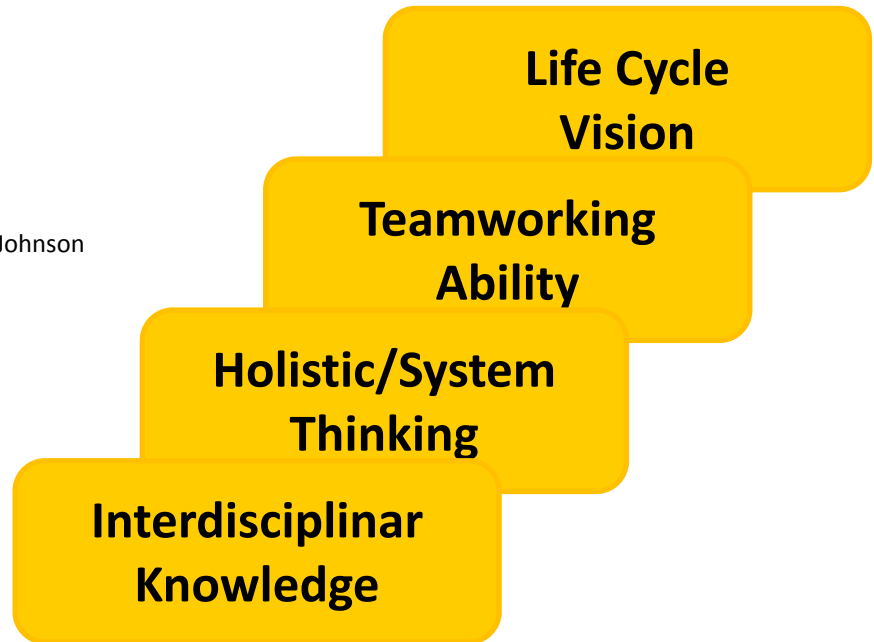


## Systems Engineering to the rescue

**"novelty, depth of knowledge, and heterogeneity [of the new disciplines], made it impossible for any one person to master in depth all of the skills needed..."**

**"jack-of-all-trades"  
technical generalist  
assumed critical importance."**

The United States Air Force and the Culture of Innovation, 1945–1965 - Stephen B. Johnson



## Systems Engineering to the rescue

Neither the Air Force nor Convair had the **necessary expertise** in the critical areas of **electronics, propulsion, and guidance** to manage the development effort.

To Defend and Deter: The Legacy of the United States Cold War Missile Program - John C. Lonquest, and David F. Winkler - United States Army Construction Engineering Research Laboratories, 1996

The **Strategic Missiles Evaluation Committee ("Teapot Committee")** proposed creating a new "**development-management**" group composed of an "***an unusually competent group of scientists and engineers*** capable of making ***systems analyses, supervising the research phases*** and completely ***controlling the experimental and hardware phases of the program***"

"Necessity as the Mother of Convention: Developing the ICBM, 1954-1958", Davis Dyer, BUSINESS AND ECONOMIC HISTORY, Fall 1993

## Systems Engineering to the rescue



**General Bernard A. Schriever**  
**Western Development Division (WDD)**



**Simon Ramo**  
**Dean Wooldridge**  
**Ramo-Wooldridge Corporation**



# What, How?

## Systems Engineering to the rescue **Communications - Documentation**



Bell Telephone Laboratories *performed research and development for AT&T.*

Bell Labs researchers typically assigned hardware **prototype manufacturing** to Western Electric, AT&T's manufacturing arm.



Because of the large size of the corporation and the multiplicity of projects, **Bell Lab and Western Electric developed formal specifications** and paperwork to handle the relationship between Bell Labs researchers and Western Electric engineers and manufacturing workers.

# What, How?

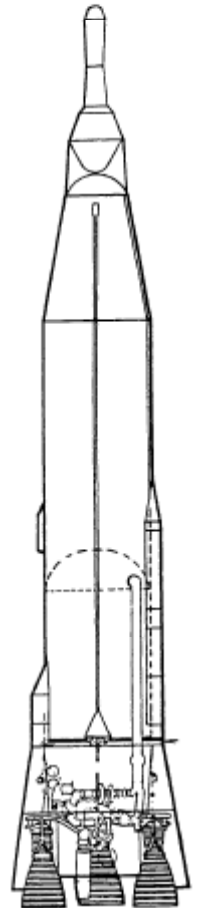
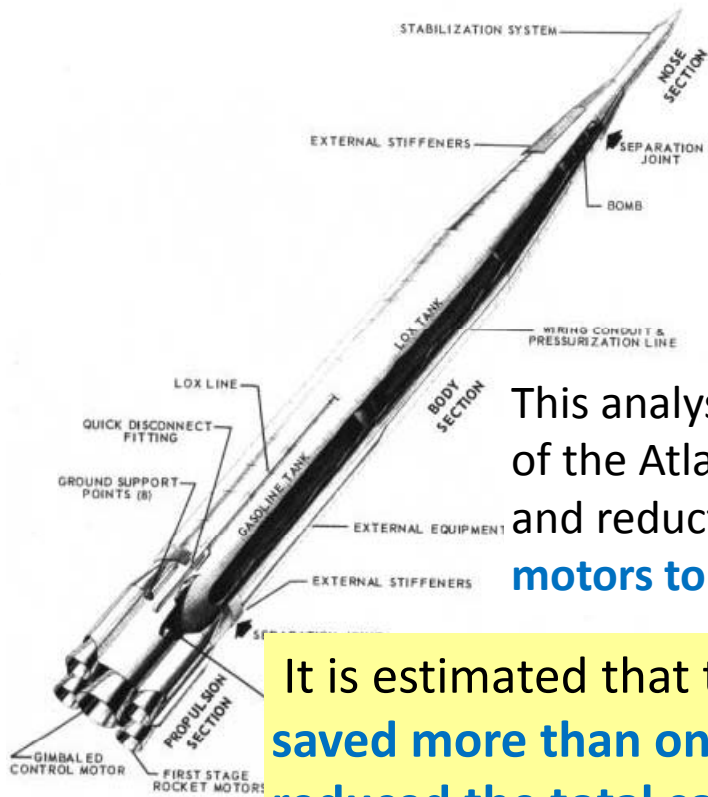
## Systems Engineering to the rescue Systems Analysis - Trade-Offs

### Nose-cone systems study

R-W personnel examined *trade-offs* between *warhead weight and yield*, *guidance accuracy*, *re-entry speed* and *thermodynamics*, *nose-cone materials*, and *other variables*.

This analysis permitted **scaling down** of the gross weight of the Atlas **from 460,000 pounds to 240,000 pounds** and reduction of the propulsion system **from five rocket motors to three**.

It is estimated that this analysis ...  
**saved more than one year of development time and reduced the total cost of the missile by a quarter.**

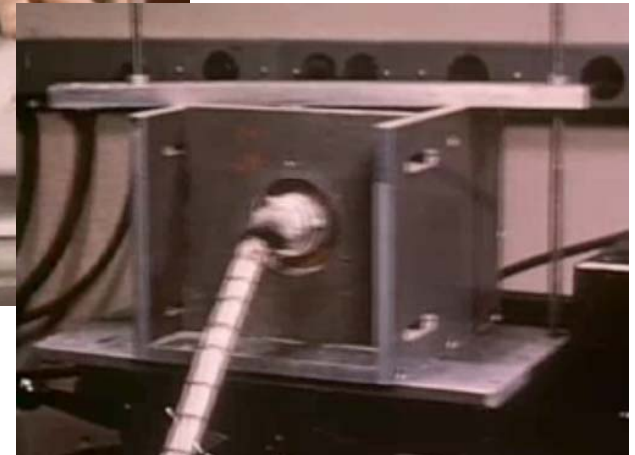
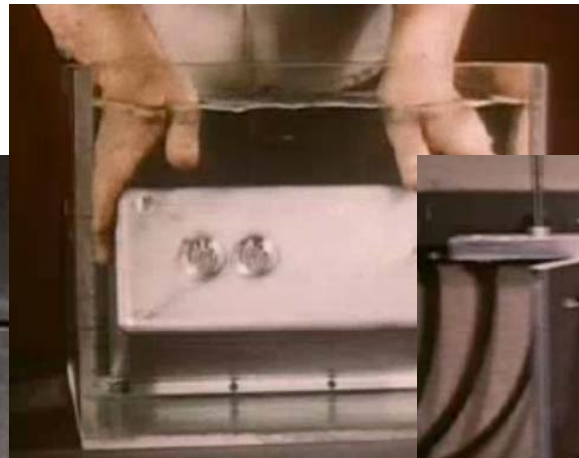
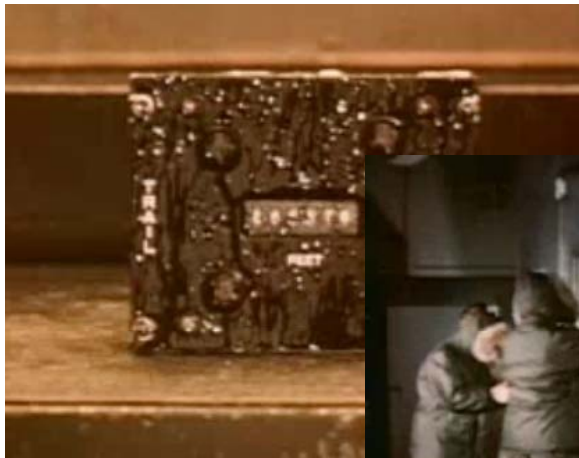


# What, How?

## Systems Engineering to the rescue **Extensive Testing**

All components underwent tests that checked environmental tolerances (temperature, humidity, and so forth), vibration tolerance, component functions, and interactions among assembled components.

The United States Air Force and the Culture of Innovation, 1945–1965 - Stephen B. Johnson



## Systems Engineering to the rescue Change Control - Configuration Management

"a number of test failures resulted from *mismatches between the design* of the missile *and the actual hardware configuration* of the missile on the launch pad"

The United States Air Force and the Culture of Innovation, 1945–1965 - Stephen B. Johnson

"**Configuration Control Board**, which had responsibility for **assuring that any necessary changes in component design would be immediately reflected throughout the total missile configuration.**"

"Necessity as the Mother of Convention: Developing the ICBM, 1954-1958", Davis Dyer, BUSINESS AND ECONOMIC HISTORY, Fall 1993



"configuration control drew **from the Boeing Company's** aircraft programs"

Samuel Phillips and the Taming of Apollo - Stephen B. Johnson, Technology and Culture, October 2001

## Systems Engineering to the rescue **System Management**



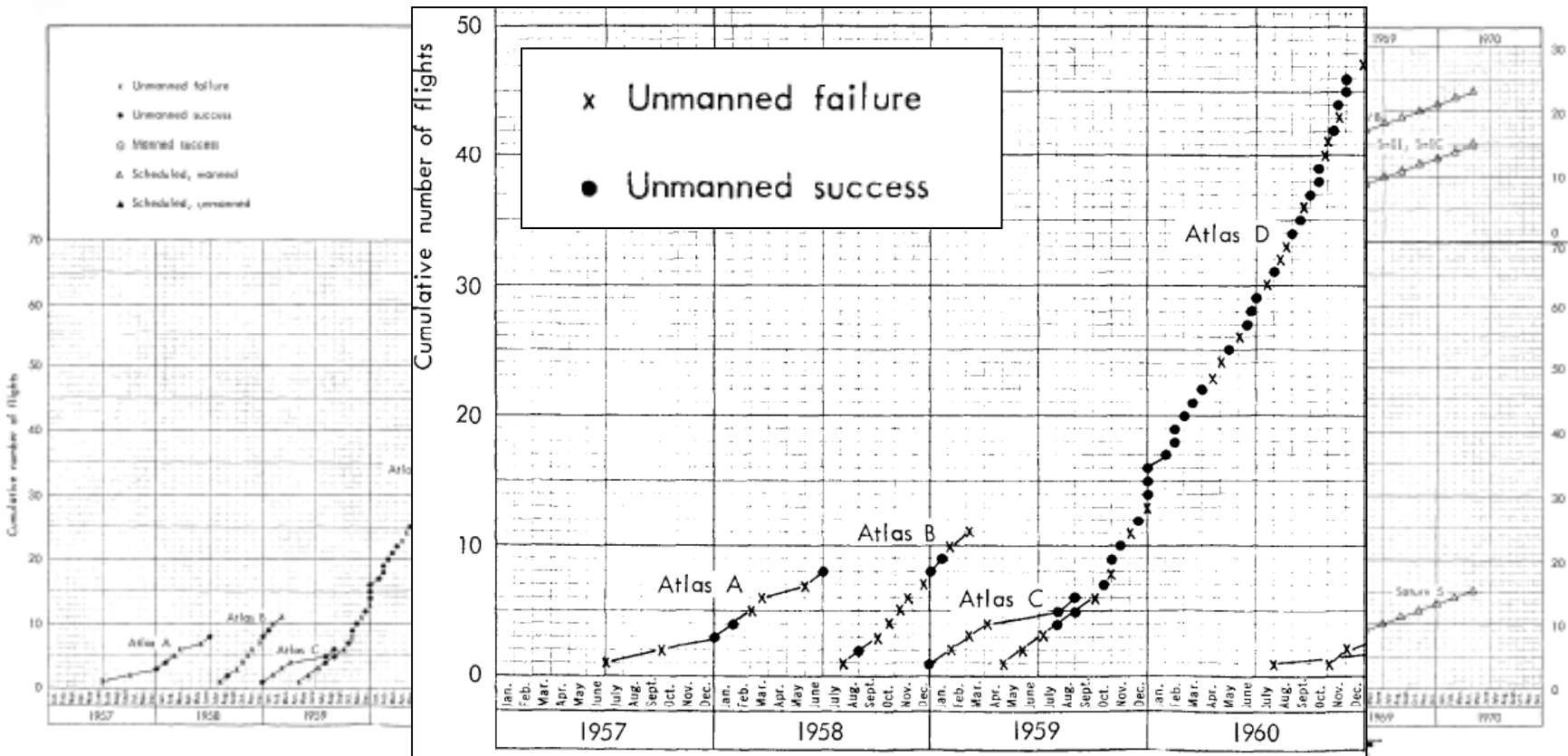
**Project Control Room:** "to serve as a **nerve center** for all project information, including hardware delivery schedules, test schedules, and operational planning schedules"

"Necessity as the Mother of Convention: Developing the ICBM, 1954-1958", Davis Dyer, Business and Economic History, Fall 1993



# Systems Engineering to the rescue

## *some signs of improvement*

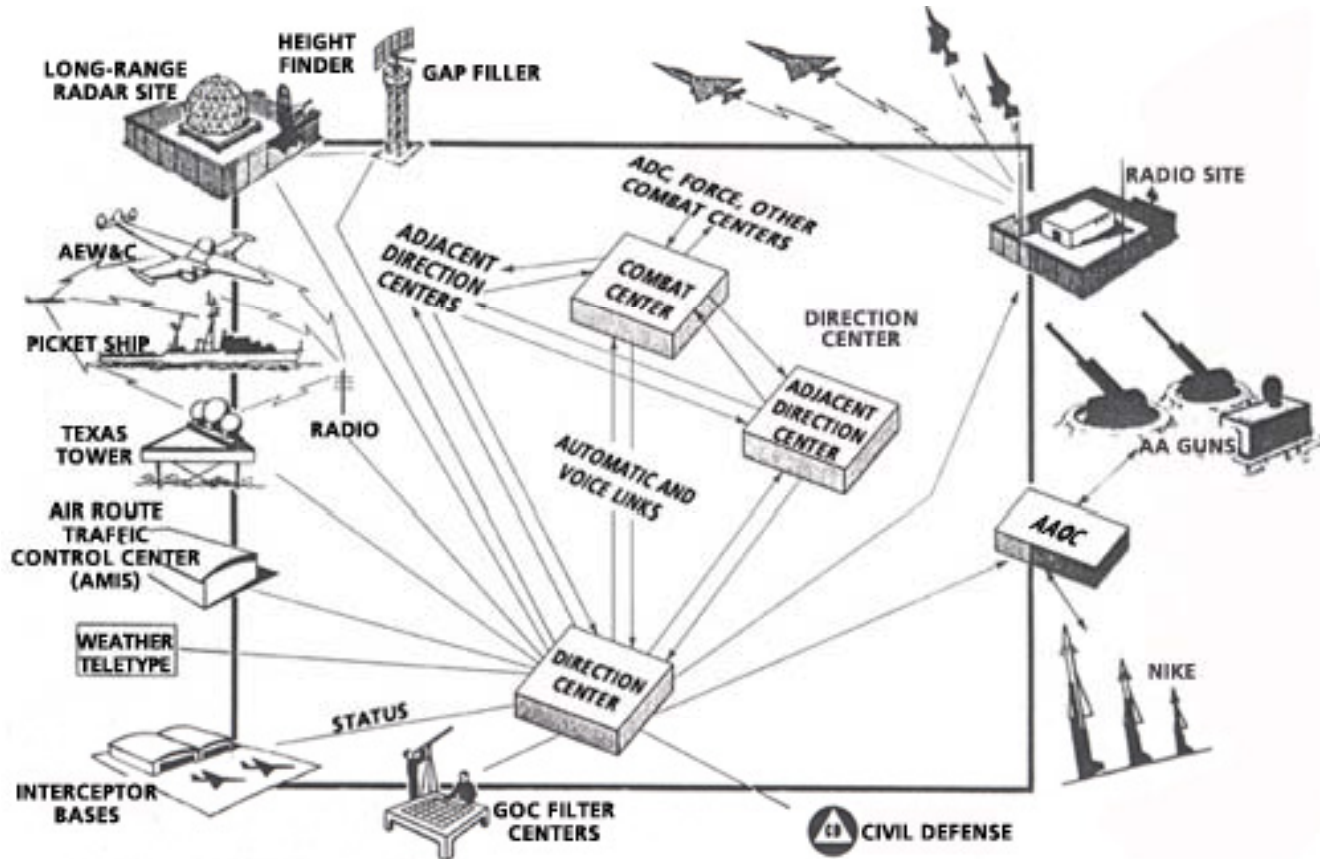


# Semi-Automatic Ground Environment (SAGE)

"first major real-time, computer-based command-and-control system.

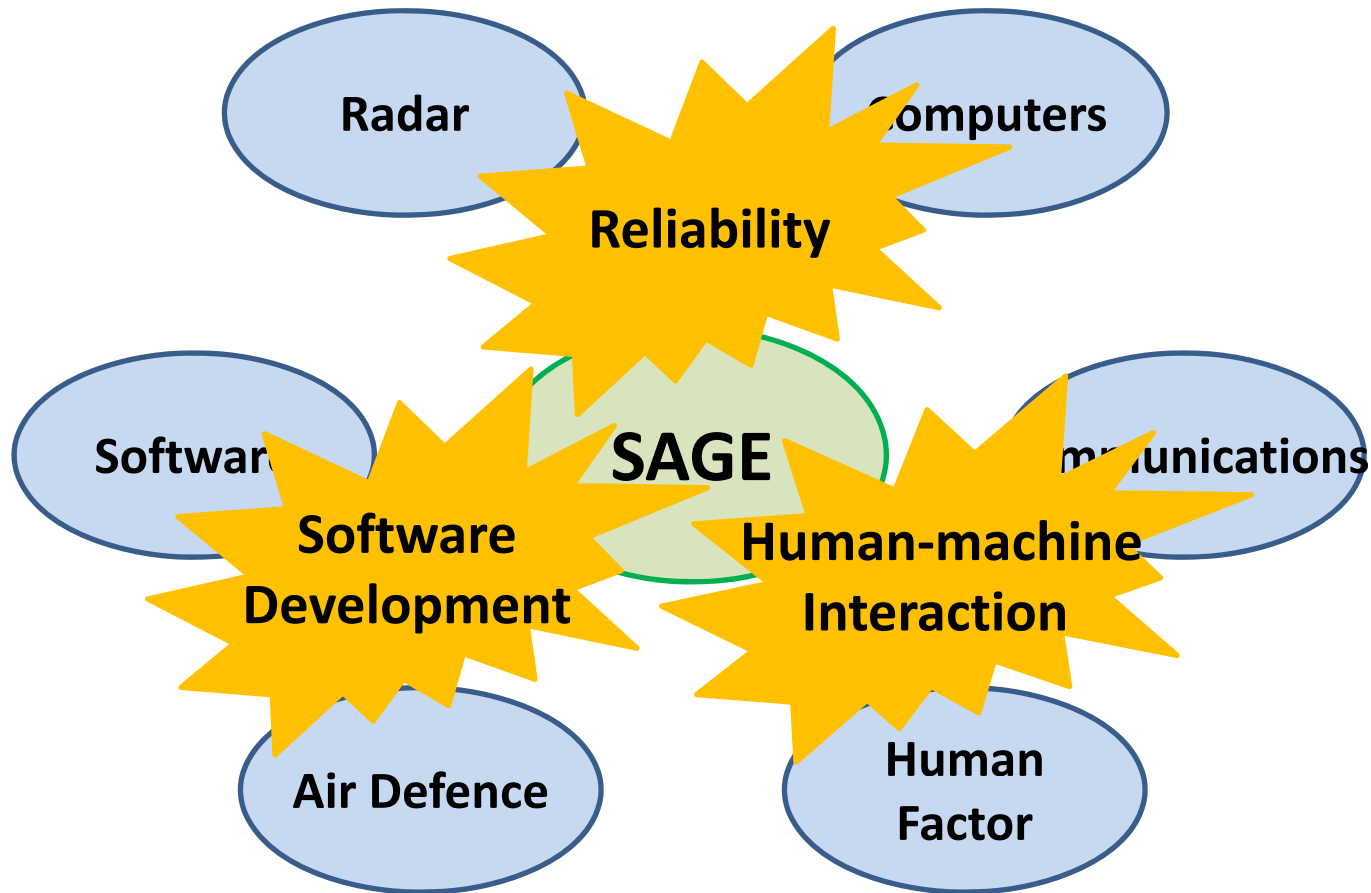
Designed to protect the United States from long range bombers "

<http://www.ll.mit.edu/news/ieee-milestone-SAGE.html>

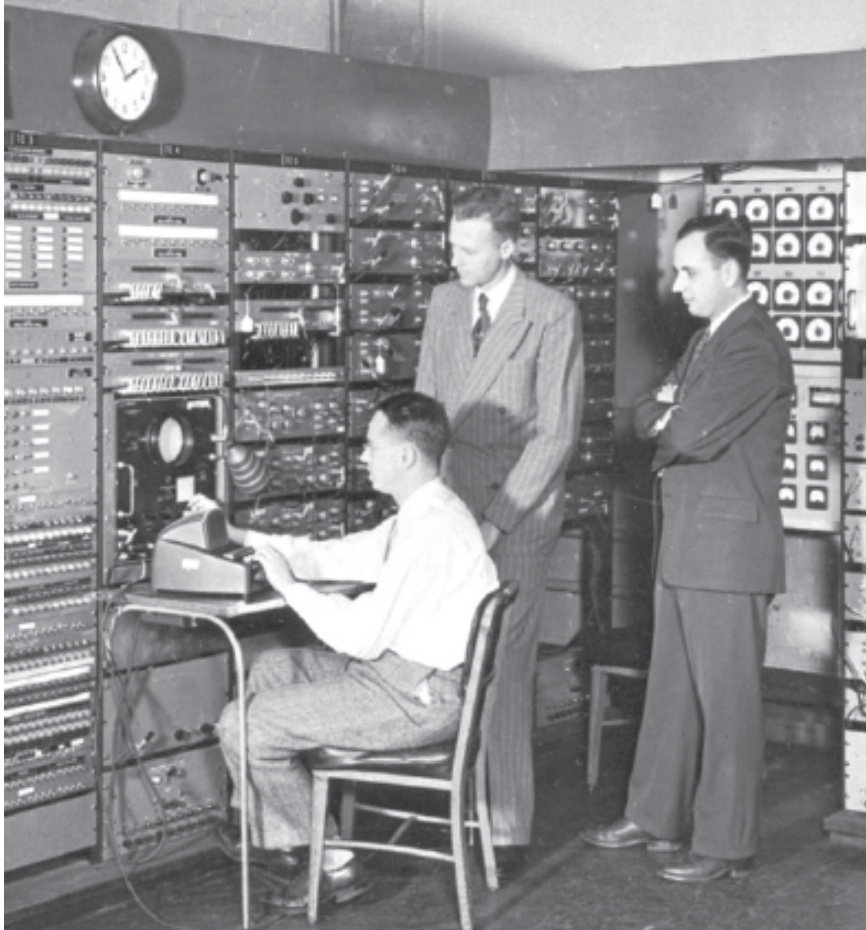


# Why?

## Multiple Technologies *UNPRECEDENTED CHALLENGES*



# Who, Where?



***MIT - Lincoln Laboratory  
Whirlwind control room  
Jay Forrester and Bob Everett (standing)***

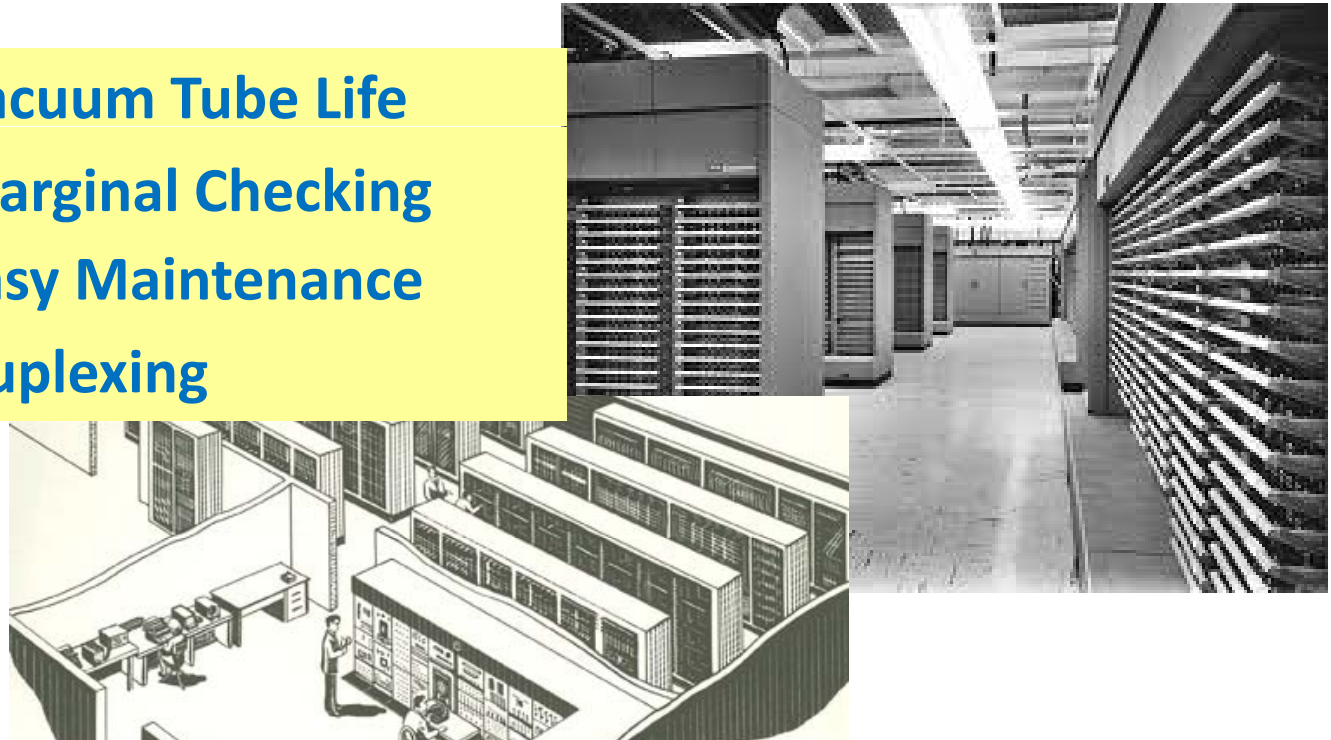


The pioneers of SAGE, Dr. **Jay Forrester** (left) and **Robert Everett** (right) at the IEEE Milestone Award ceremony (27 June 2012)

# What, How?

## Systems Engineering to the rescue **Reliability (systemic approach)**

- Vacuum Tube Life
- Marginal Checking
- Easy Maintenance
- Duplexing



between June and November 1955, the computer operated on a 24-hour, 7-day schedule with **97.8% reliability**

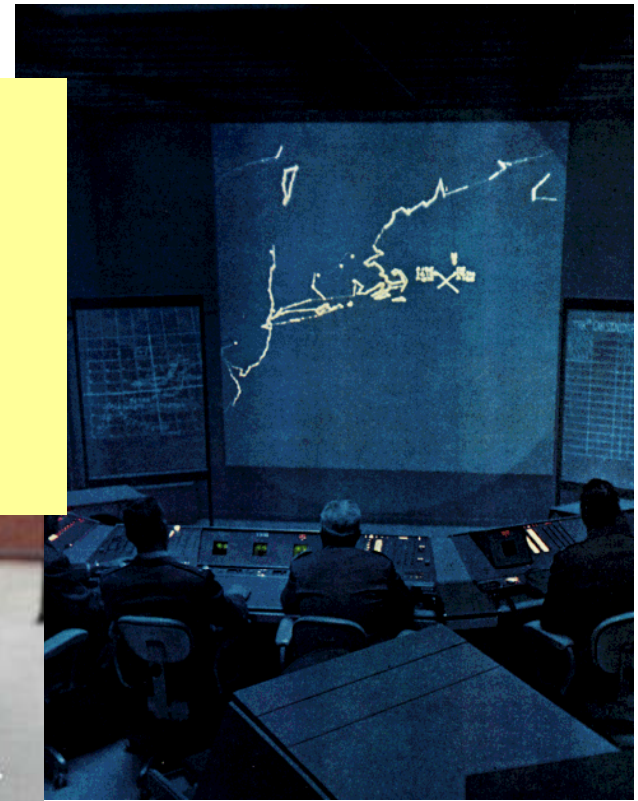
MIT Lincoln Laboratory: History:Early Digital Computing [http://www.ll.mit.edu/about/History/digitalcomputing\\_2.html](http://www.ll.mit.edu/about/History/digitalcomputing_2.html)



# What, How?

## Systems Engineering to the rescue **Human System Integration**

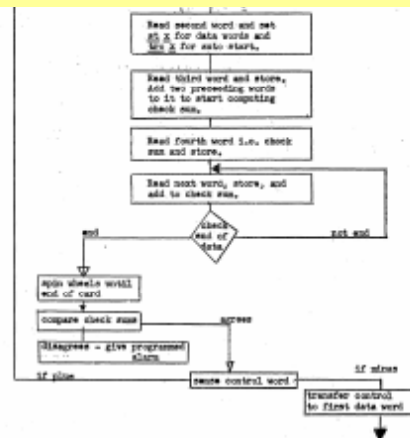
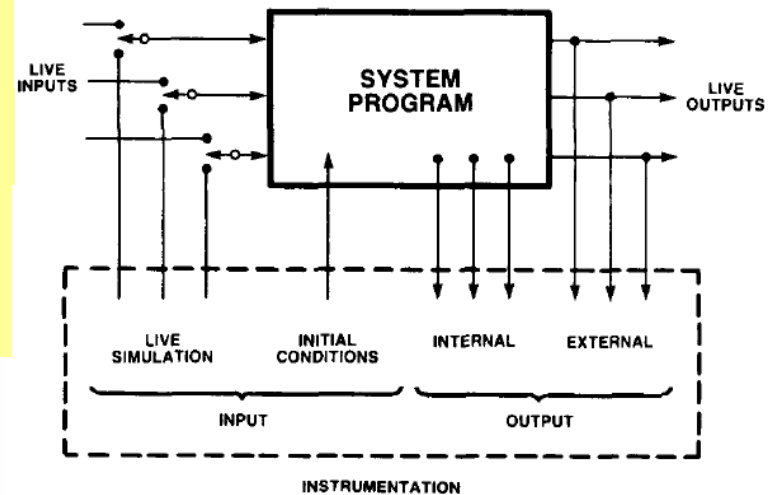
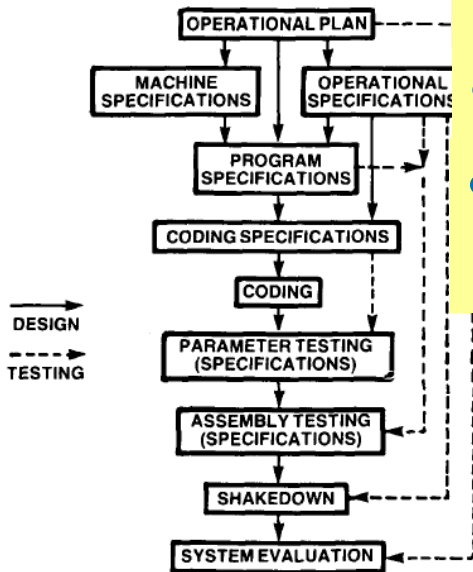
- interactive graphic displays,
- light-pen input
- training (virtual simulations)



# What, How?

## Systems Engineering to the rescue Software Development (method and documentation)

- process and documentation
- thorough testing
- problem-reporting procedure



# Systems Engineering reaching maturity

## APOLLO Program

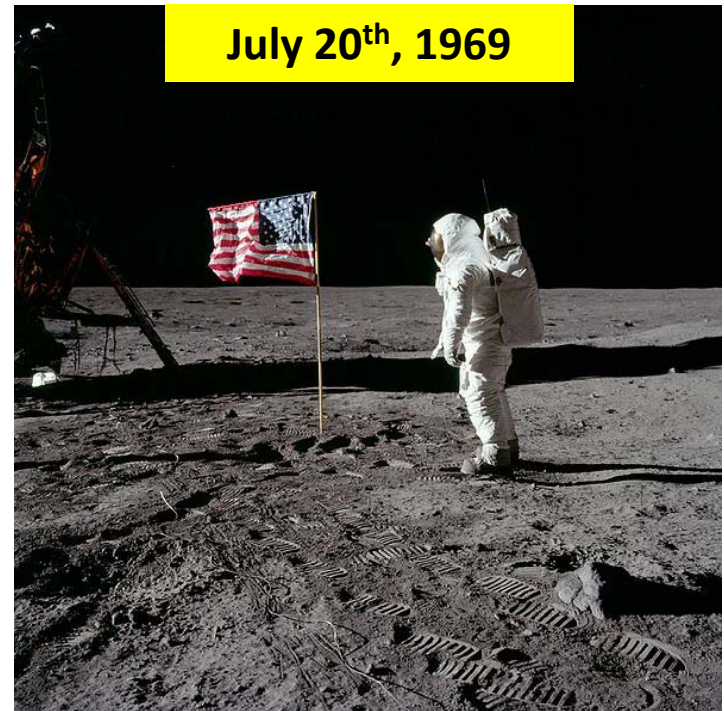
May 25, 1961



First, I believe that this nation should commit itself to achieving the goal, **before this decade is out, of landing a man on the moon and returning him safely to the earth.**

Special Message to the Congress on Urgent National Needs, President John F. Kennedy

July 20<sup>th</sup>, 1969



**"Houston, Tranquility base here. The eagle has landed."**



## APOLLO Program

A huge partnership to achieve a common goal



"All you see [are] the three of us, but beneath the surface are thousands and thousands of others."

Apollo 11 astronaut Michael Collins



At its peak, the Apollo program employed **400,000 Americans** and required the support of over **20,000** industrial firms and universities.

<http://www.nasa.gov/centers/langley/news/factsheets/Apollo.html>

Did the application of system engineering contribute to the success of Apollo **on schedule, within budget, and with mission success?**

**The evidence supports an unqualified "yes."**

"Systems Engineering – A Retrospective View." - James H. Brill, Systems Engineering, Vol. 1, No. 4, 1999



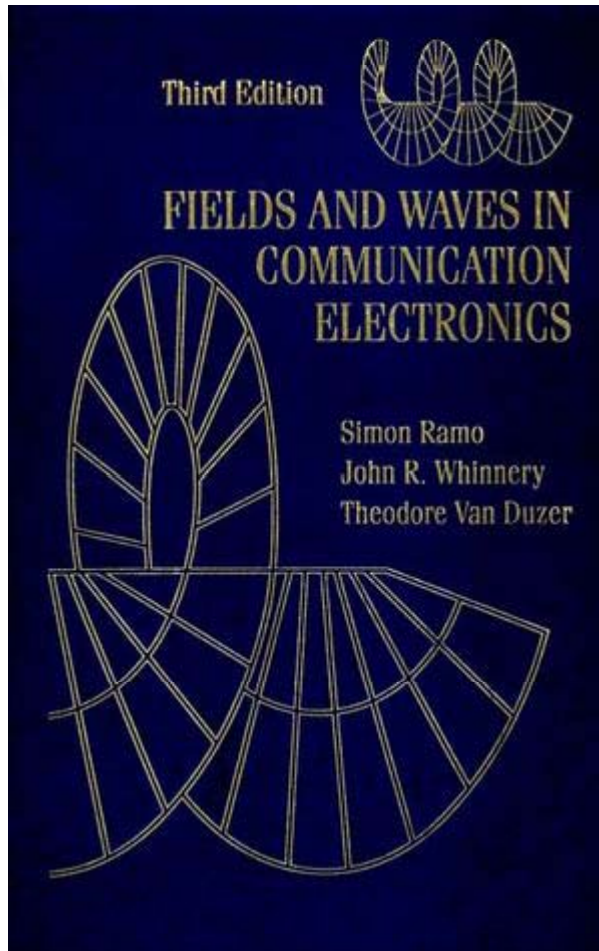
## The winning trait of Systems Engineering

**"systems engineering is just plain common sense** in that each concept, each step, is the reasonable thing to do.

**The value of the systems approach is that it allows you to bring all these common-sense ideas together in concert to focus on the resolution of complex problems in complex environments"**

Systems Concepts: Lectures On Contemporary Approaches To Systems - Ralph F. Miles, Wiley, 1973

# Who?



## **Simon Ramo**

"globally recognized as a leader in microwave research and headed the development of GE's Electron microscope. He also published textbooks on Fields and Waves in Modern Radio (1944) and Introduction to Microwaves (1945)"

<http://edisontechcenter.org/SimonRamo.htm>

# Who?



**Jay Forrester**

A pioneer in early digital computer development ..., Forrester invented random-access magnetic-core memory. He also pioneered the growing field of system dynamics.

Forrester is the *Professor Emeritus of Management in System Dynamics* at the MIT Sloan School of Management.

# Who?



## **Wernher von Braun**

"one of the most important rocket developers and champions of space exploration"; "leader of ... the "rocket team" which developed the V-2 ballistic missile". " chief architect of the Saturn V launch vehicle ... that would propel Americans to the Moon "

<http://history.msfc.nasa.gov/vonbraun/bio.html>

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