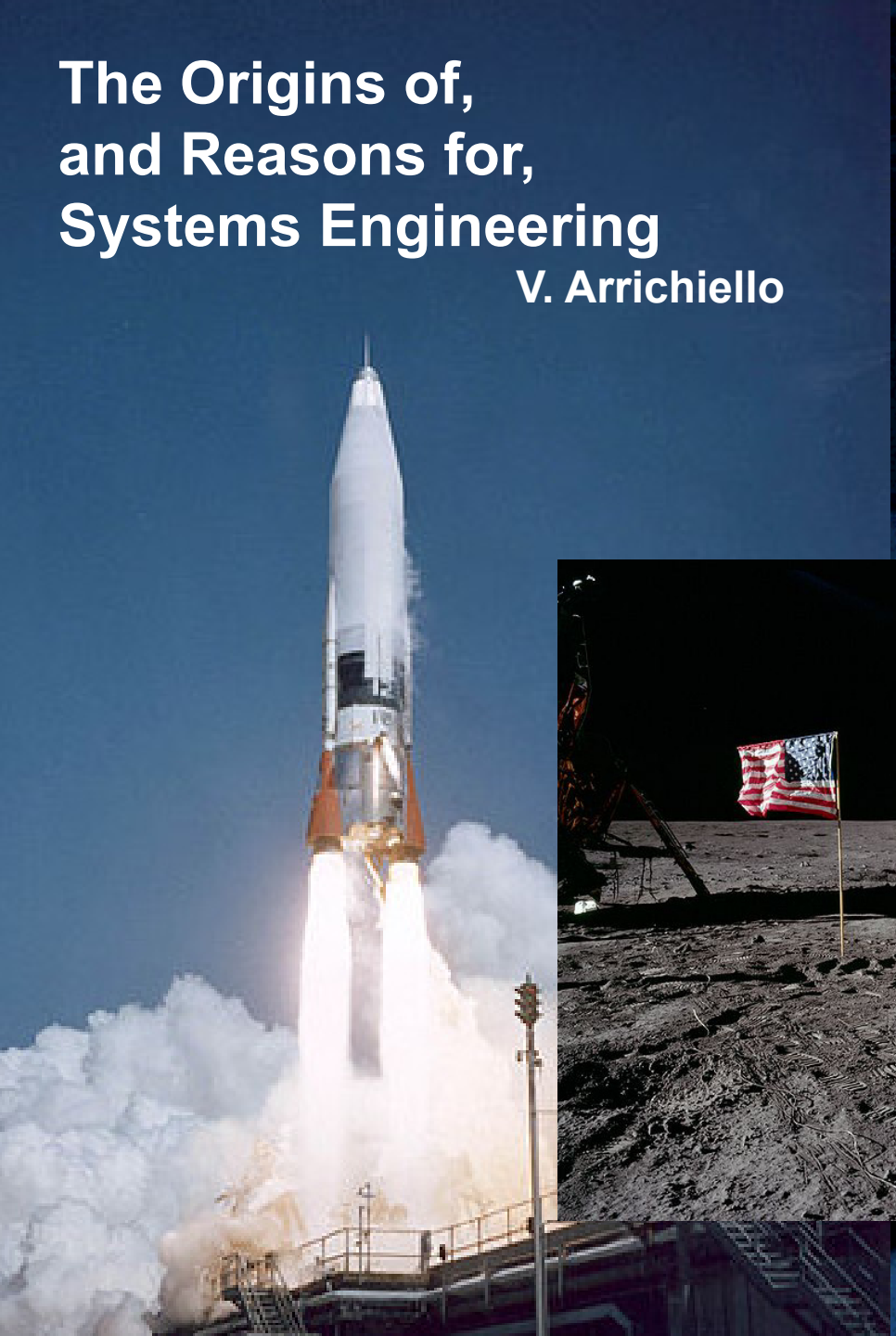
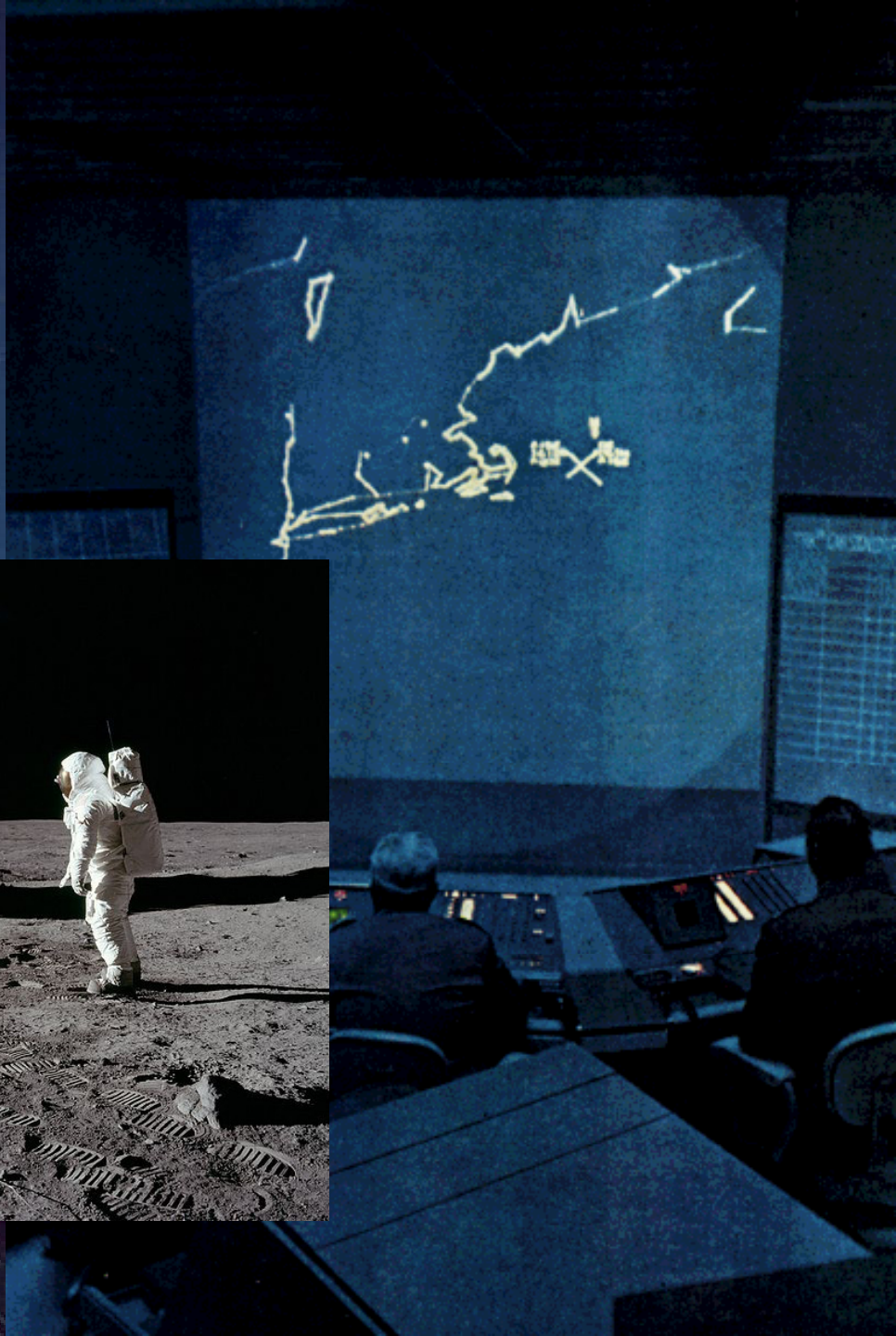
The Origins of, and Reasons for, Systems Engineering

V. Arrichiello





Systems Engineering

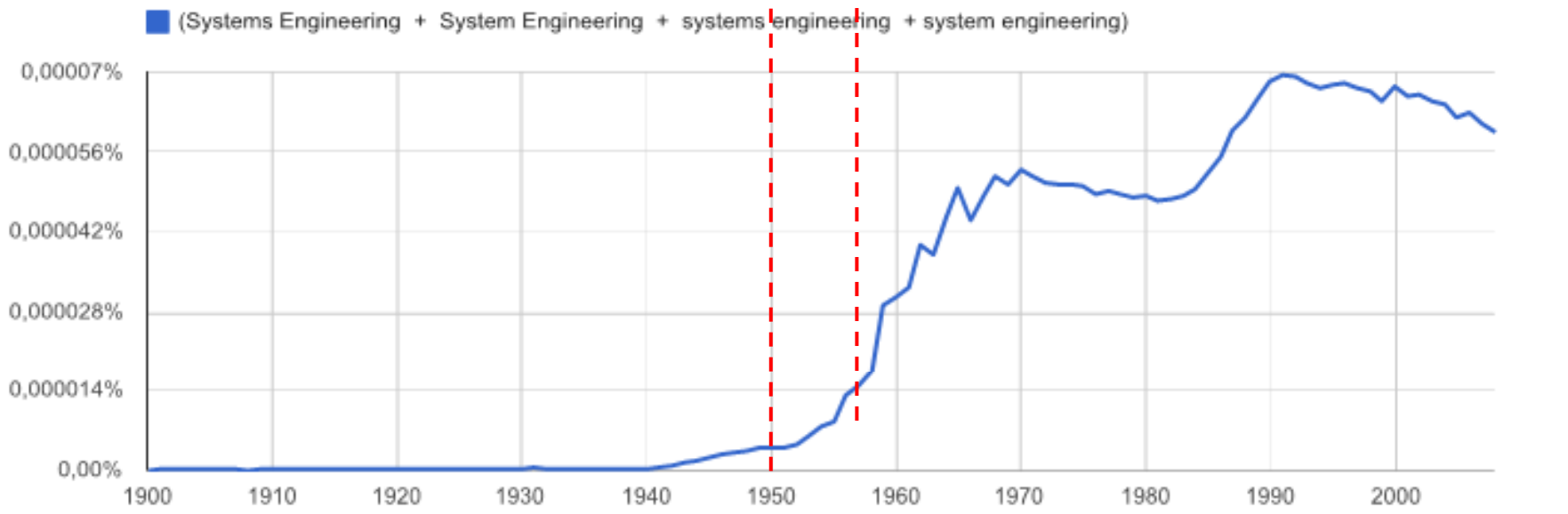
WHEN?
WHY?
WHO?
WHERE?
WHAT?
HOW?

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



Google books Ngram Viever

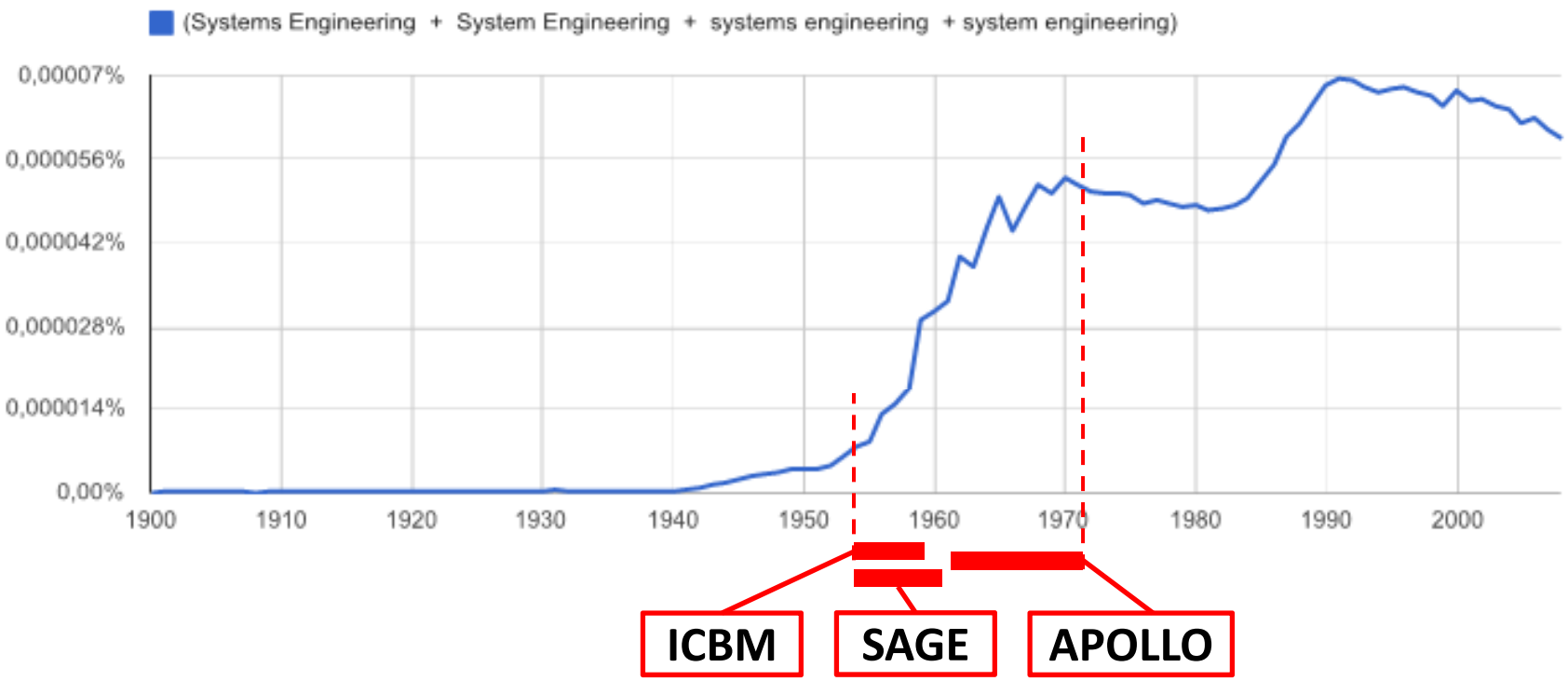
When?

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)

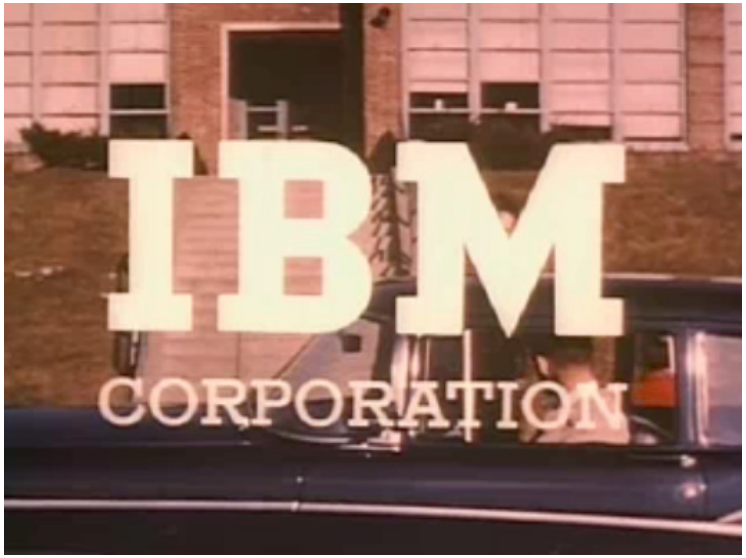
When?

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

When?

Historical Context

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

When?

Historical Context

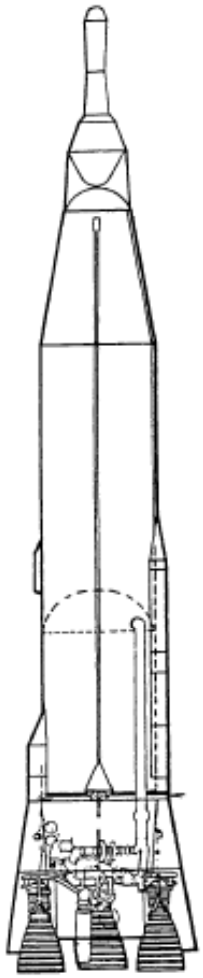
"On Guard! The Story of SAGE",
IBM Corporation, Military Products Division, (ca. 1956),
The Internet Archive, Prelinger Archives

When?

Historical Context

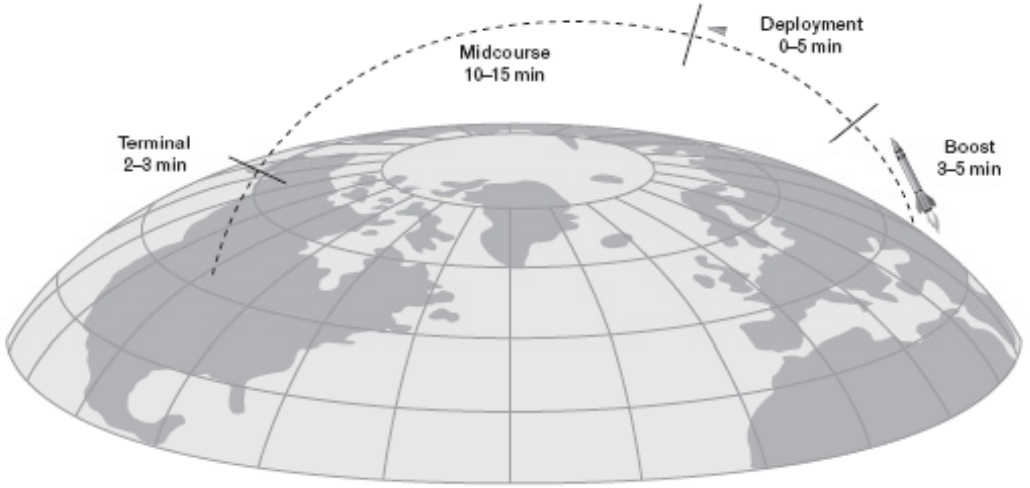
"On Guard! The Story of SAGE",
IBM Corporation, Military Products Division, (ca. 1956),
The Internet Archive, Prelinger Archives

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

Why?

A Dangerous Mix

Novel, heterogeneous technologies

Why?

A Dangerous Mix

Novel, heterogeneous technologies

Complexity

Why?

A Dangerous Mix

Novel, heterogeneous technologies

Cold War technological race

Complexity

Why?

A Dangerous Mix

Novel, heterogeneous technologies

Cold War technological race

Complexity

Compressed Time -scale

Why?

A Dangerous Mix

Novel, heterogeneous technologies

Cold War technological race

Complexity

Failure rate

Compressed Time -scale

Why?

A Dangerous Mix

Novel, heterogeneous technologies

Cold War technological race

Complexity

Failure rate

Compressed Time -scale

Why?

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

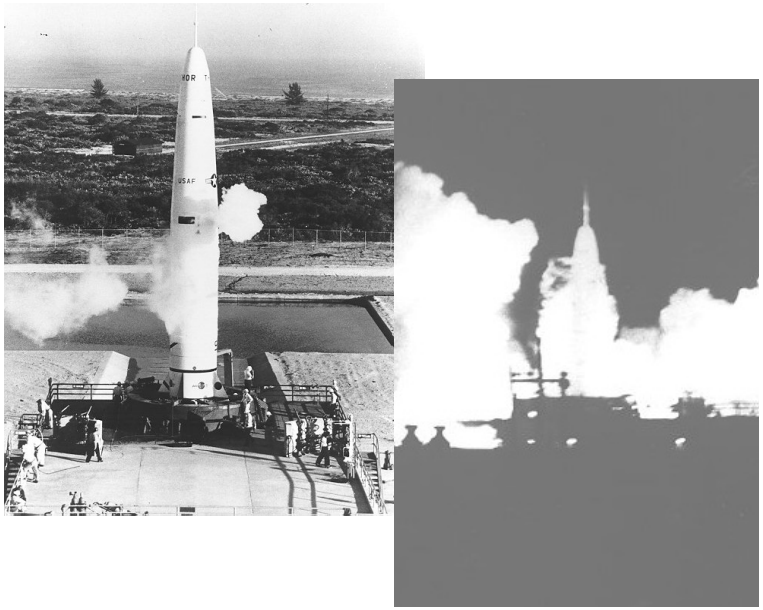
The United States Air Force and the Culture of Innovation, 1945–1965 - Stephen B. Johnson

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

Why?

"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

Why?

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

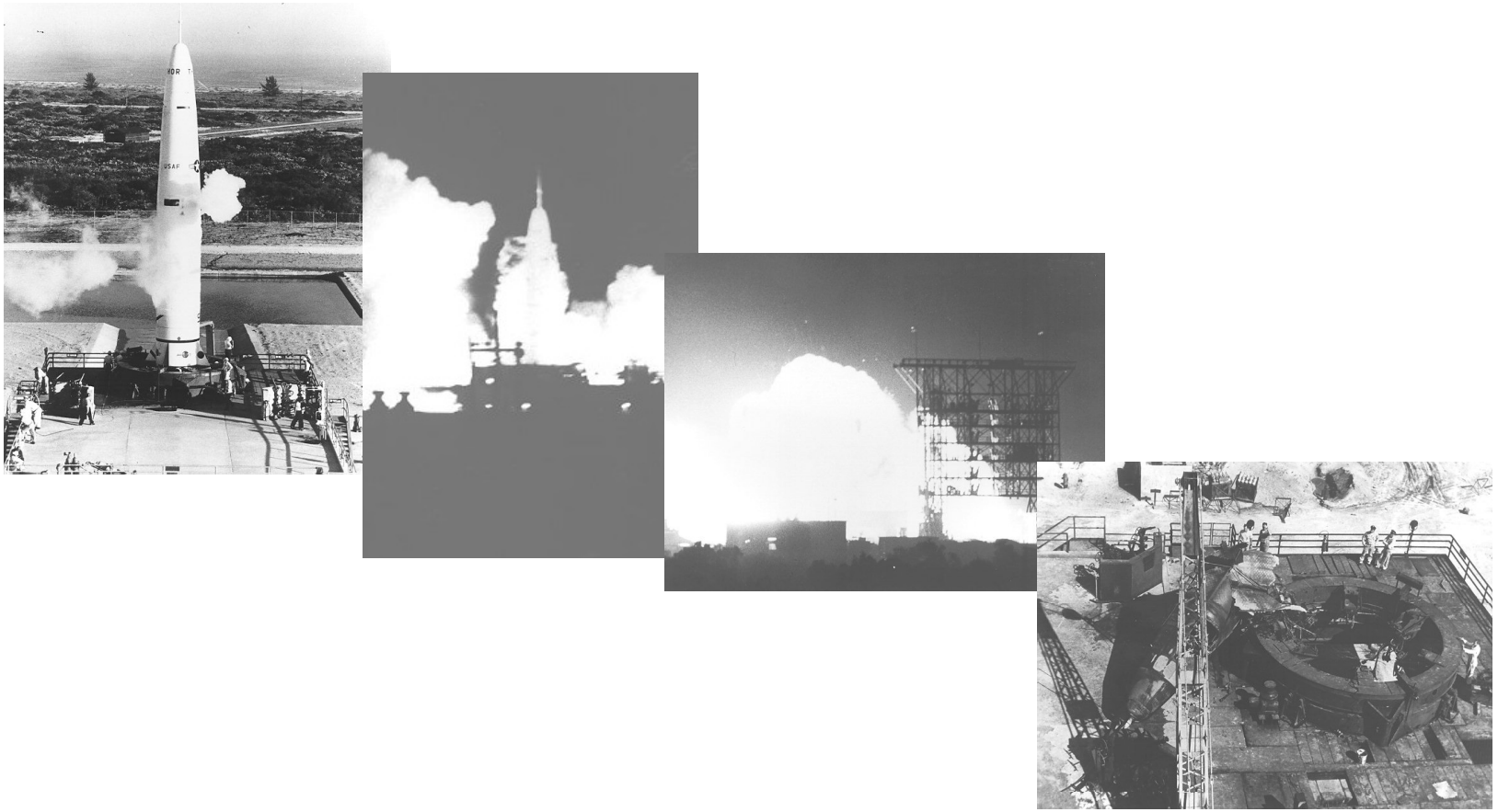
The United States Air Force and the Culture of Innovation, 1945–1965 - Stephen B. Johnson

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

Why?

"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

Why?

"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

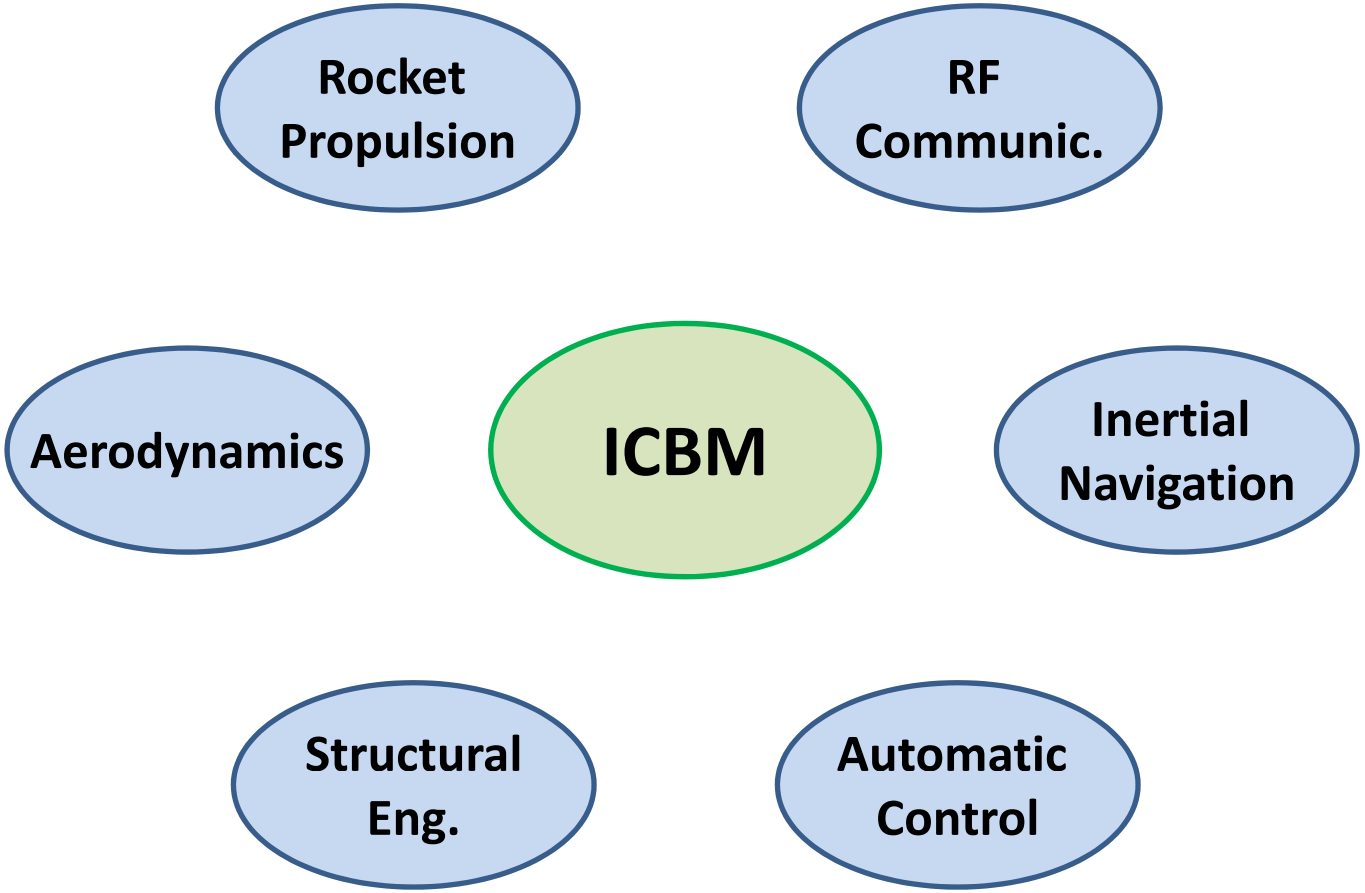
- Thor 101...reached an ***apogee of 6 inches*** whereupon...slid backwards...and **exploded**...
- Thor 102 **flight lasted 35 seconds**...
- Thor 103...**exploded** on the pad...
- Thor 104...**broke up** after 92 seconds...

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

http://en.wikipedia.org/wiki/PGM-17_Thor

Why?

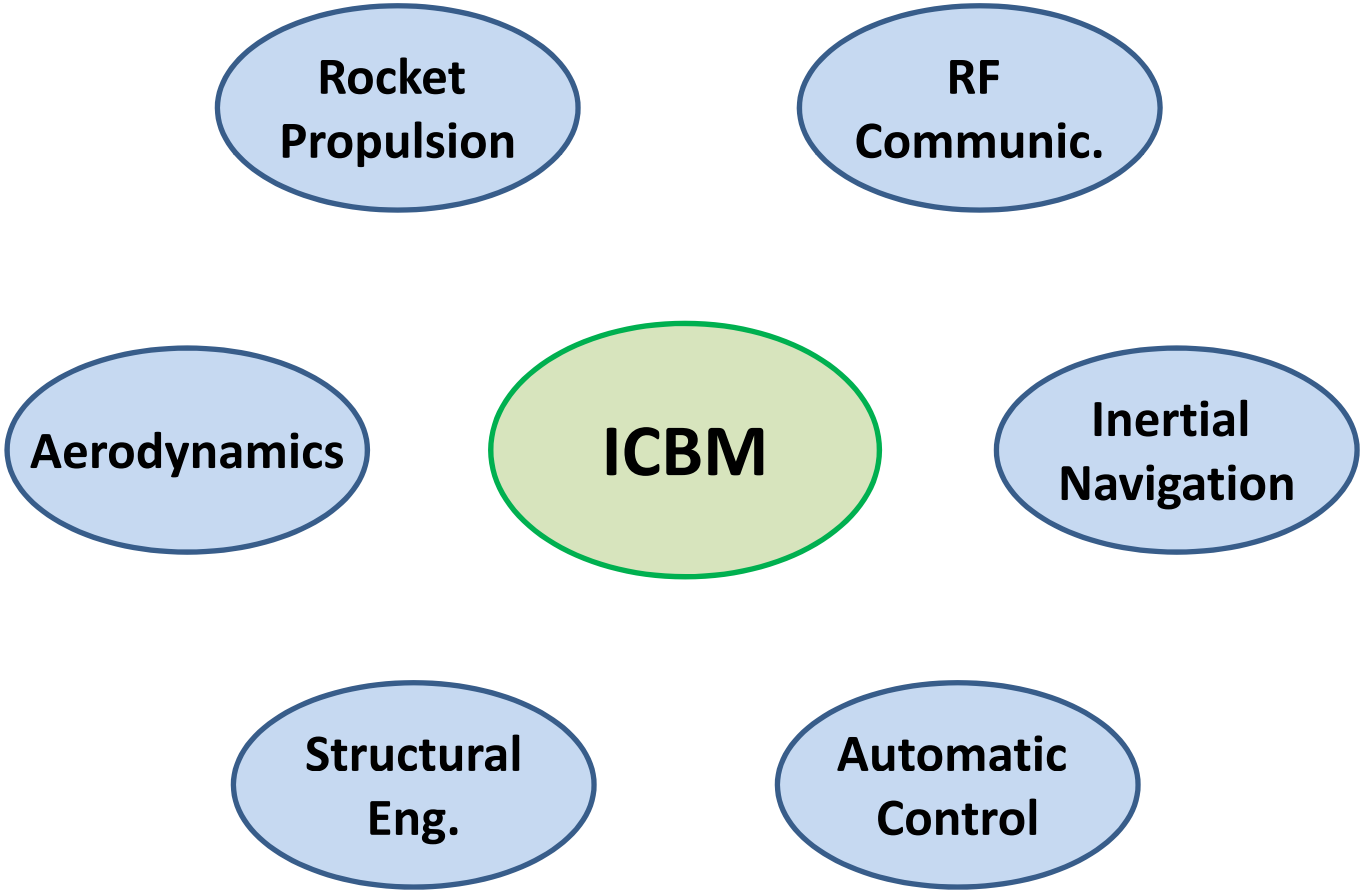
Multiple Technologies



Why?

Multiple Technologies

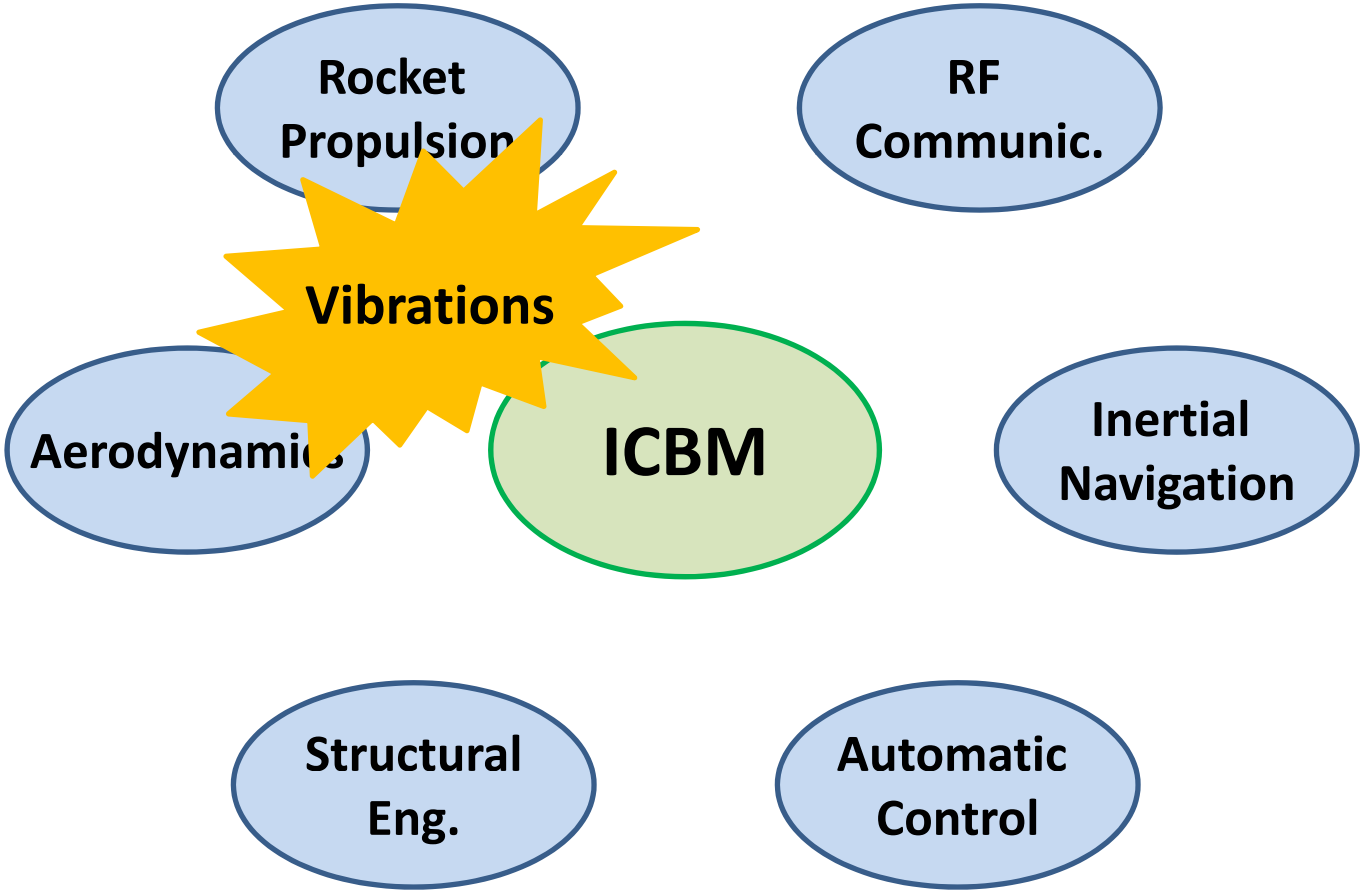
ADVERSE INTERACTIONS



Why?

Multiple Technologies

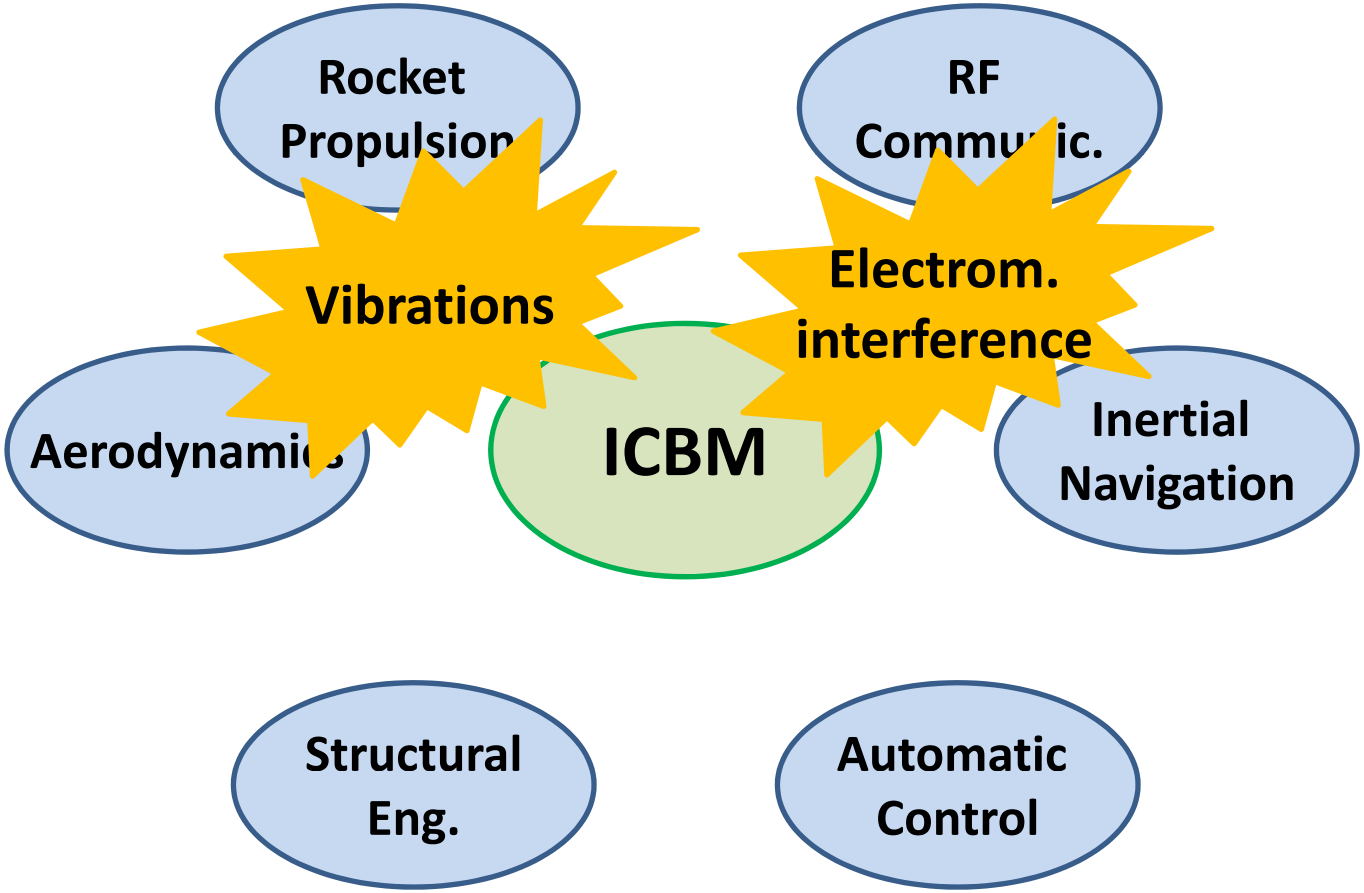
ADVERSE INTERACTIONS



Why?

Multiple Technologies

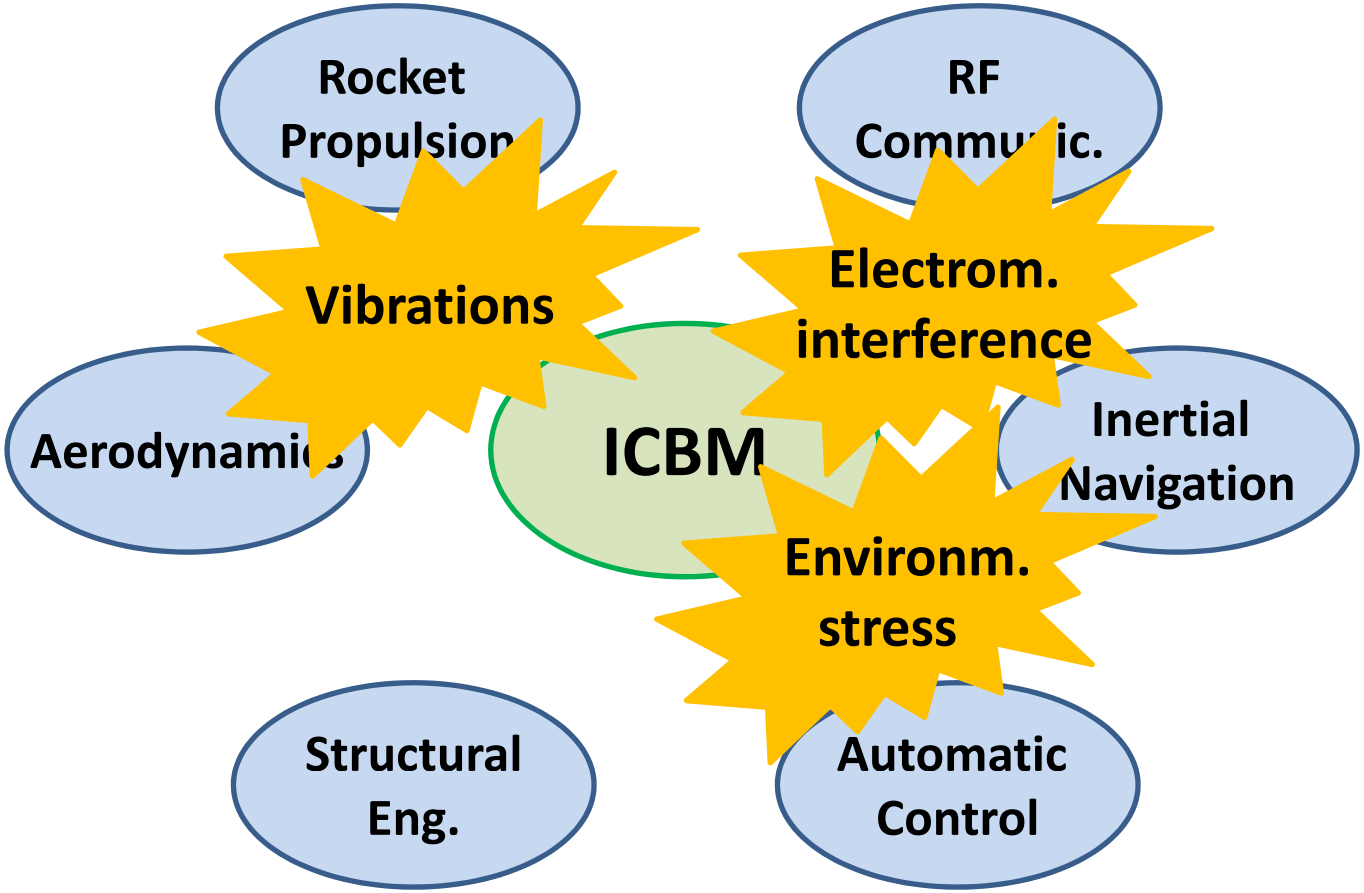
ADVERSE INTERACTIONS



Why?

Multiple Technologies

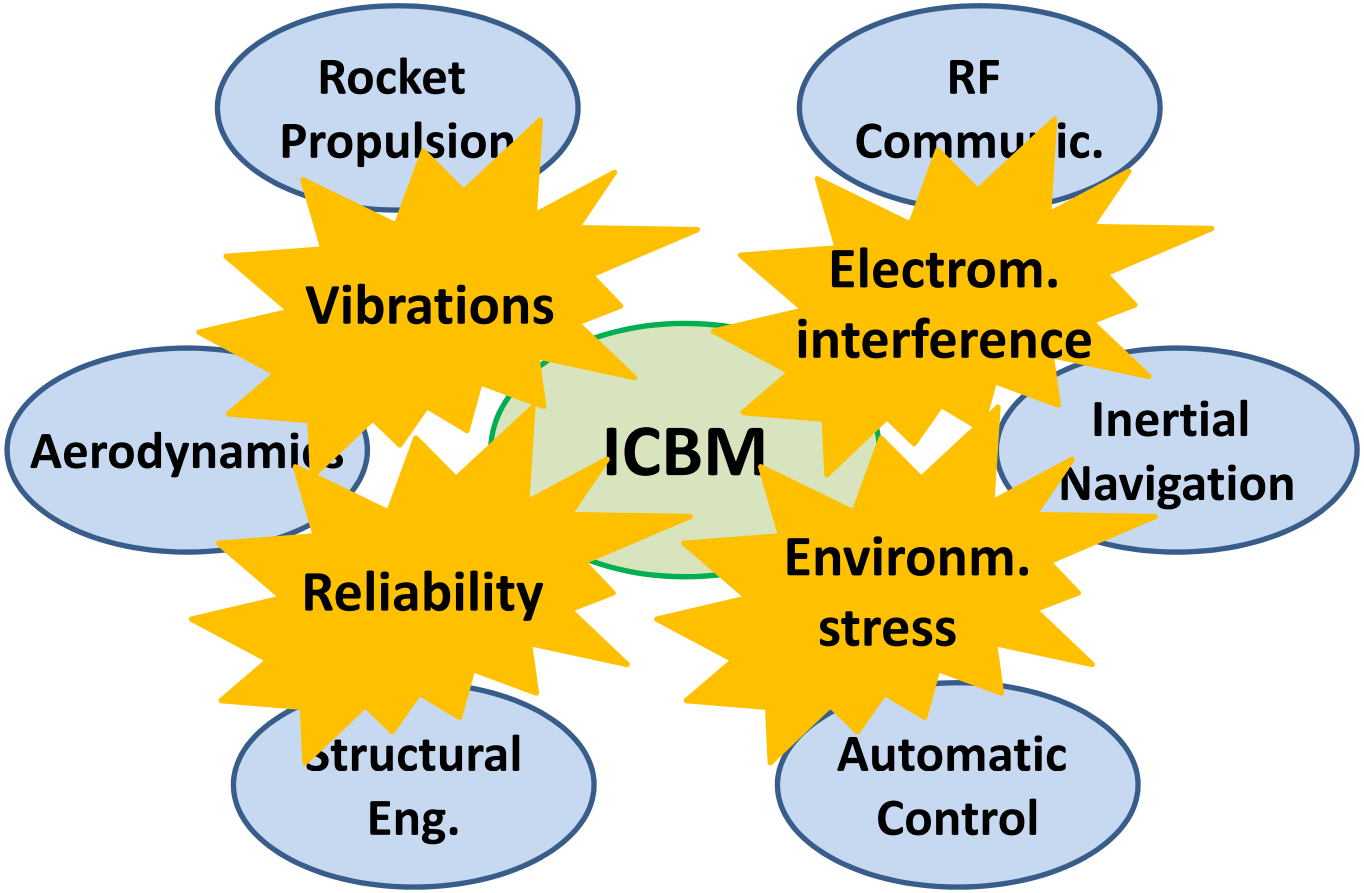
ADVERSE INTERACTIONS



Why?

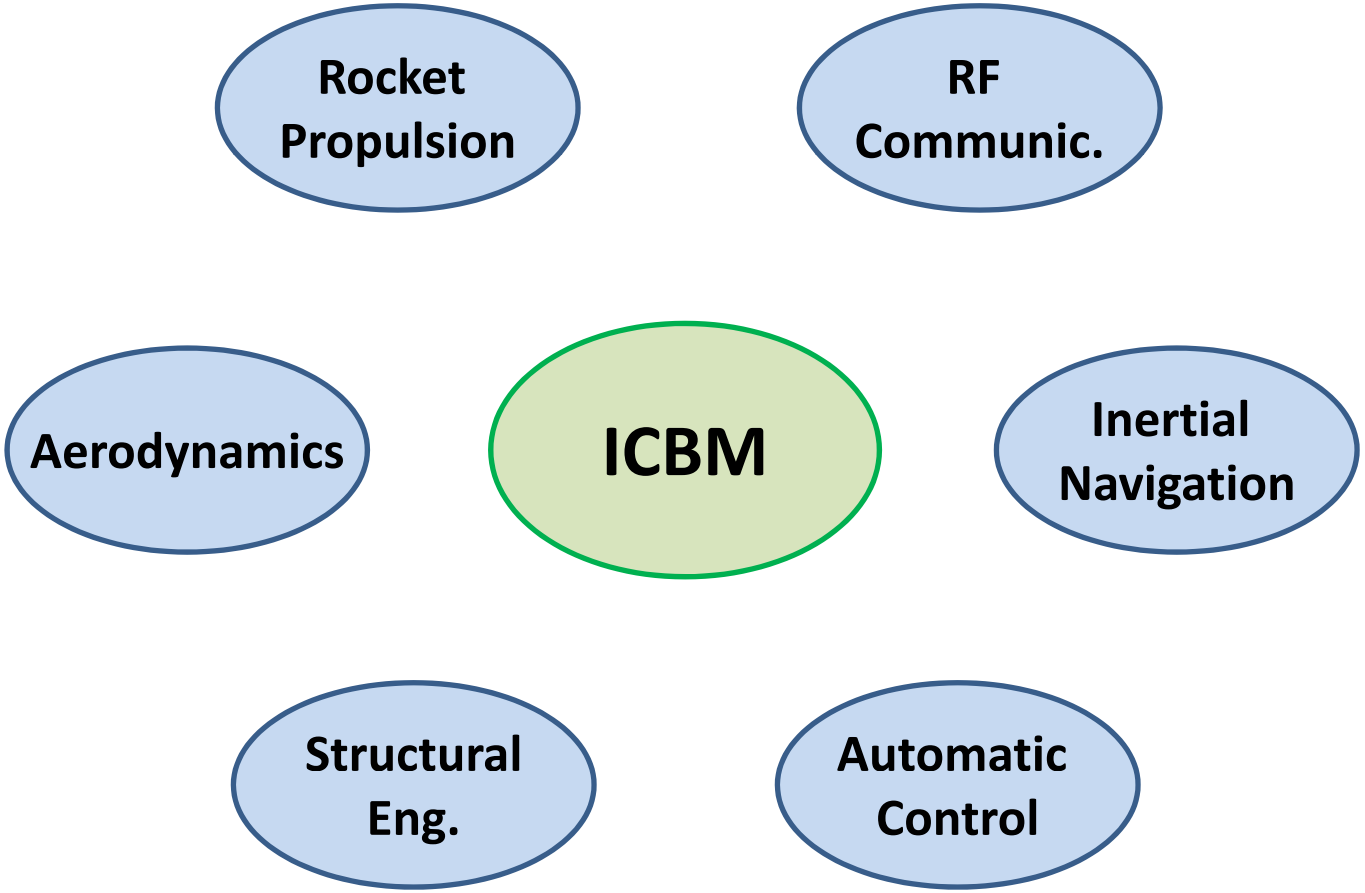
Multiple Technologies

ADVERSE INTERACTIONS



Why?

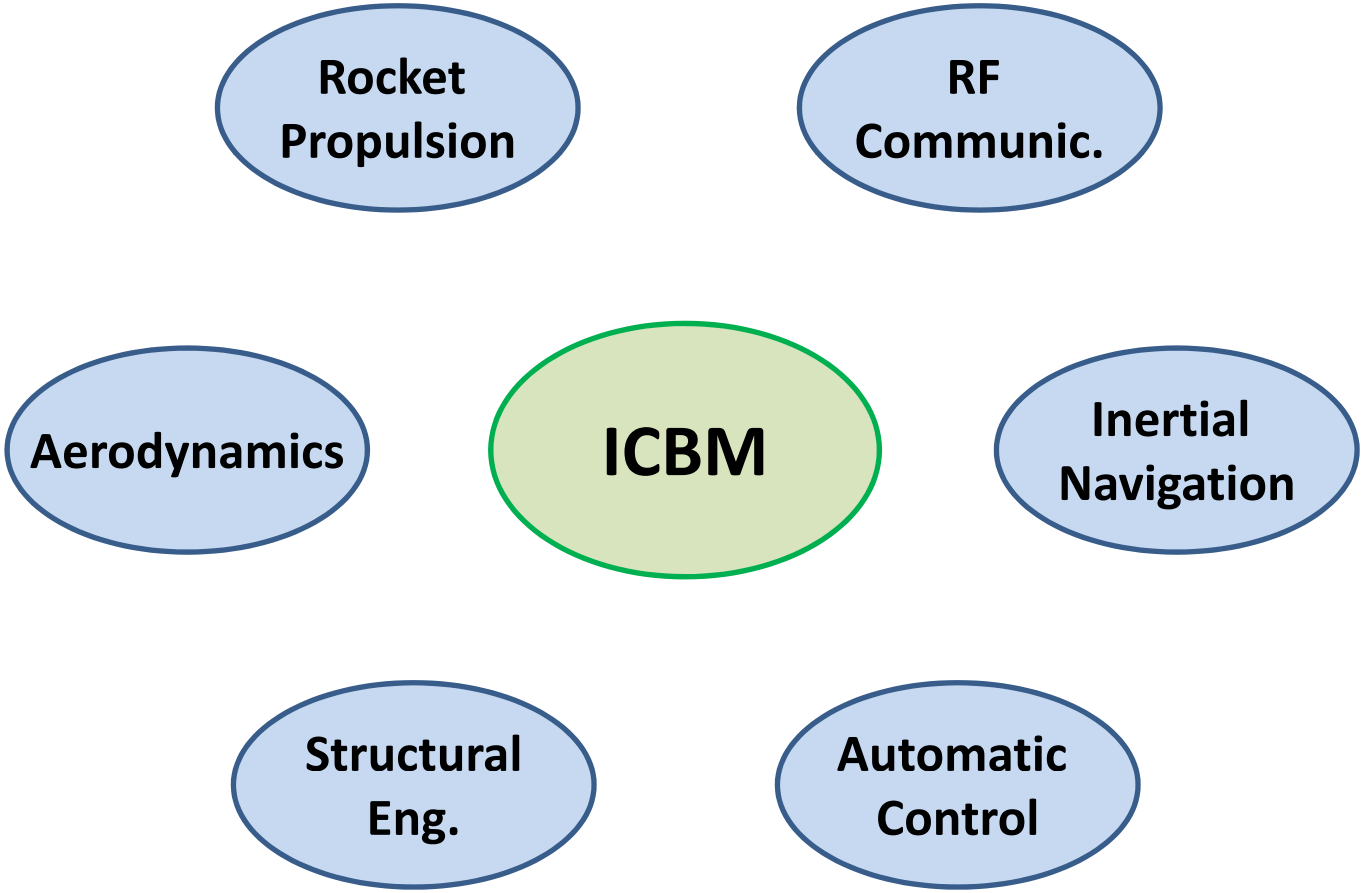
Multiple Technologies



Why?

Multiple Technologies

POOR COMMUNICATIONS



Why?

Multiple Technologies

POOR COMMUNICATIONS

Rocket Propulsion

RF Communic.

Aerodynami

Pieter Bruegel de Oude, De toren van Babel

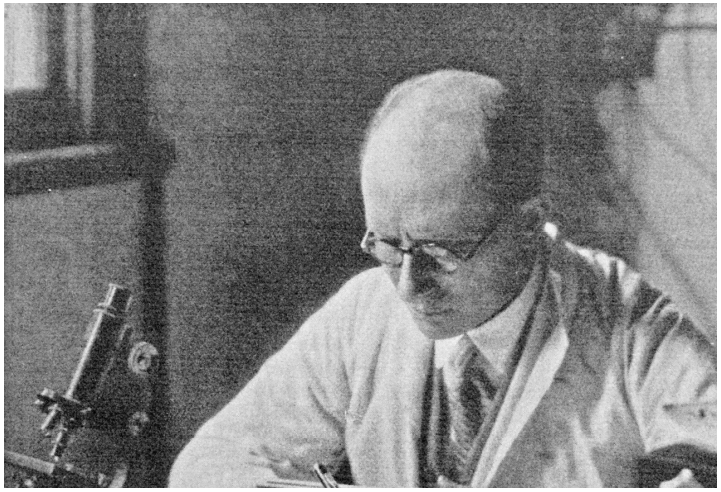
Inertial Navigation

Structural Eng.

Automatic Control

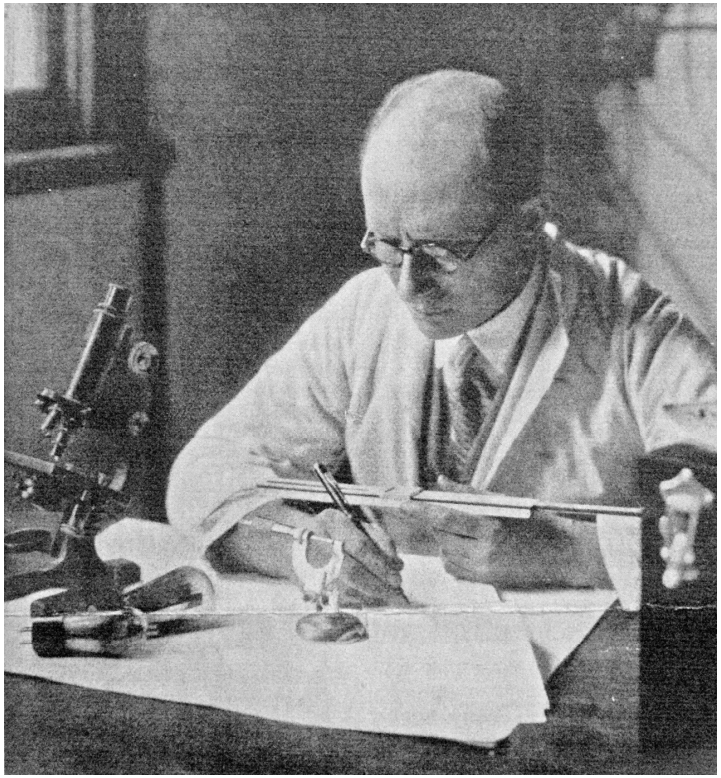
Why?

Diverse worlds



Why?

Diverse *engineering* worlds

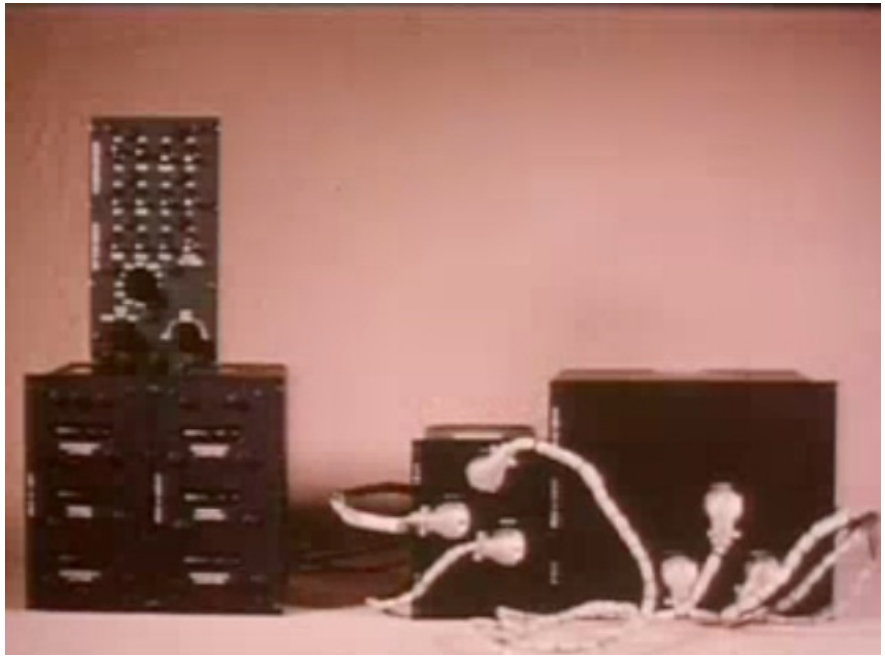


Joseph Griffith Reed
Radio Pioneer

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

Who, Where?

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

Who, Where?

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

Interdisciplinar Knowledge

Who, Where?

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

Holistic/System Thinking

Interdisciplinar Knowledge

Who, Where?

Systems Engineering to the rescue

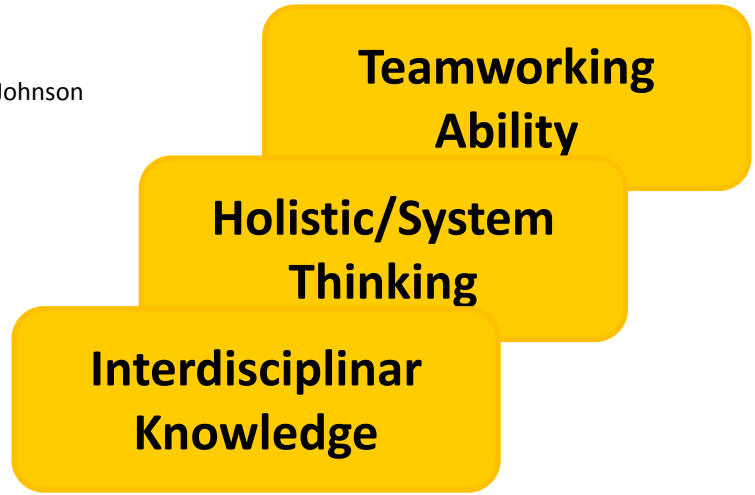
"**novelty, depth of knowledge, and heterogeneity** [of the new disciplines], **made it impossible for any one person to master in depth all of the skills needed...**

“jack-of-all-trades”

technical generalist

assumed critical importance."

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



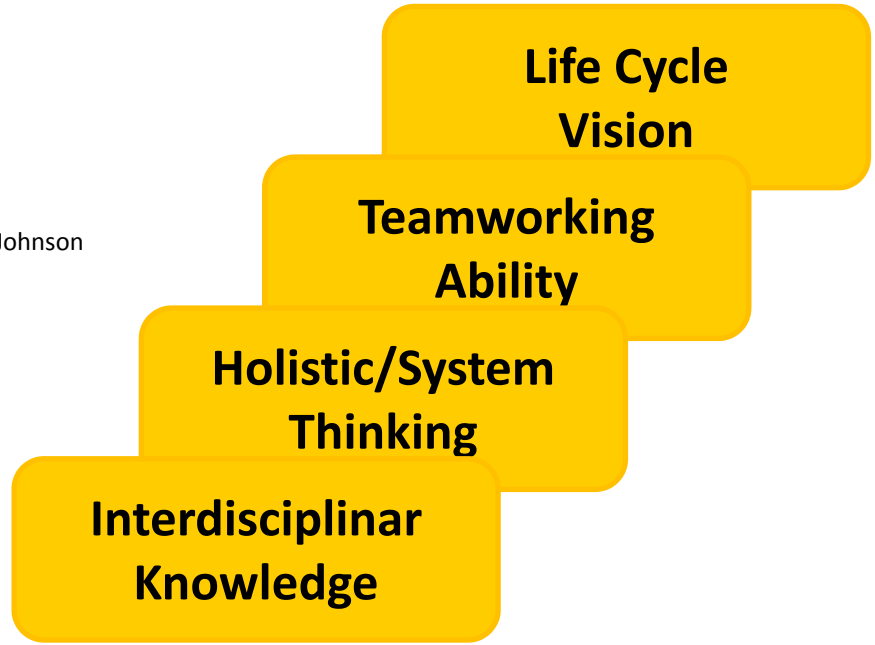
Who, Where?

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



Who, Where?

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. Lonnquest, and David F. Winkler - United States Army Construction Engineering Research Laboratories, 1996

Who, Where?

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. Lonnquest, 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

Who, Where?

Systems Engineering to the rescue

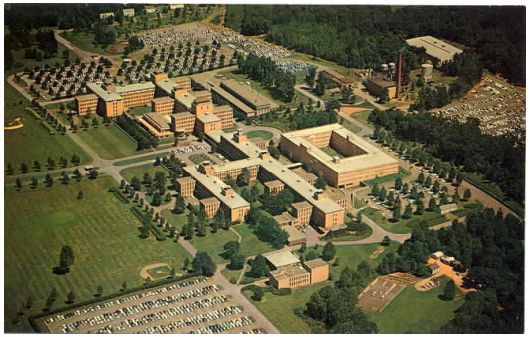
General Bernard A. Schriever
Western Development Division (WDD)

Simon Ramo
Dean Wooldridge
Ramo-Wooldridge Corporation

What, How?

Systems Engineering to the rescue

Communications - Documentation



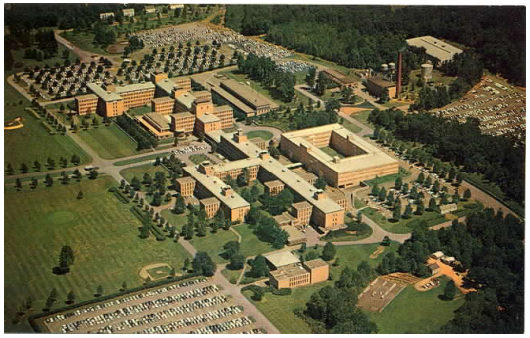
Bell Telephone Laboratories *performed* ***research and development*** *for AT&T*.

The Secret of Apollo: Systems Management in American and European Space Programs, Stephen B. Johnson, Johns Hopkins University Press, 2006

What, How?

Systems Engineering to the rescue

Communications - Documentation



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

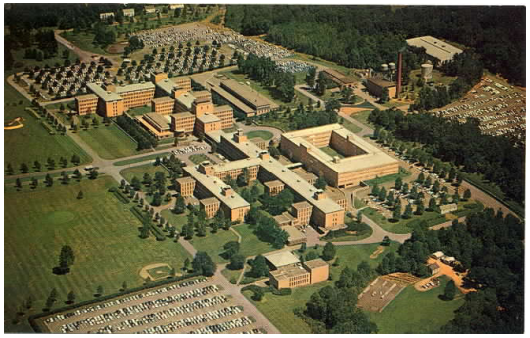
Bell Labs researchers typically assigned hardware **prototype manufacturing** to Western Electric, AT&T's manufacturing arm.

The Secret of Apollo: Systems Management in American and European Space Programs, Stephen B. Johnson, Johns Hopkins University Press, 2006

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.

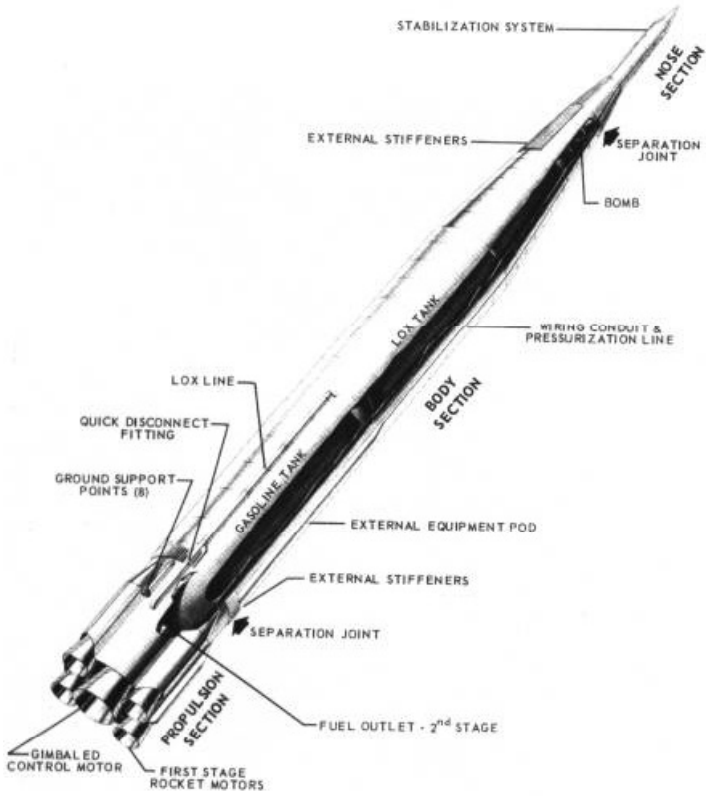
Because of the large size of the corporation and the multiplicity of projects, **Bell Lab and Western Electric developed formal specifications** and paperwork to handle the relationship between Bell Labs researchers and Western Electric engineers and manufacturing workers.

The Secret of Apollo: Systems Management in American and European Space Programs, Stephen B. Johnson, Johns Hopkins University Press, 2006

What, How?

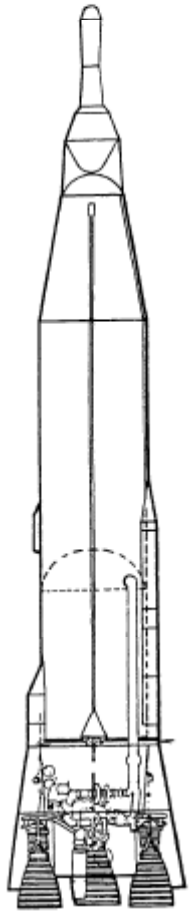
Systems Engineering to the rescue

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*.

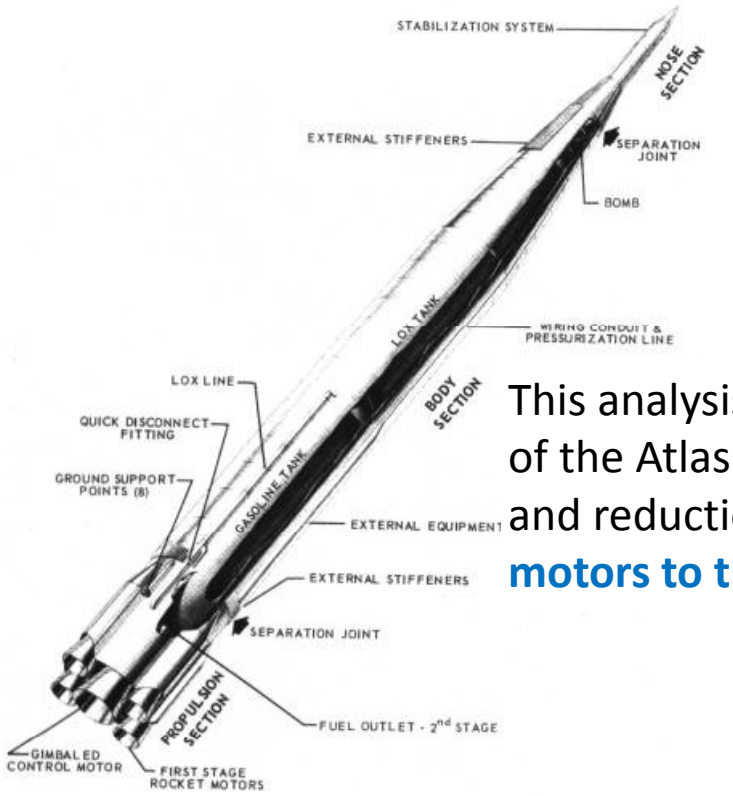


"Necessity as the Mother of Convention: Developing the ICBM, 1954-1958", Davis Dyer, BUSINESS AND ECONOMIC HISTORY, Fall 1993

What, How?

Systems Engineering to the rescue

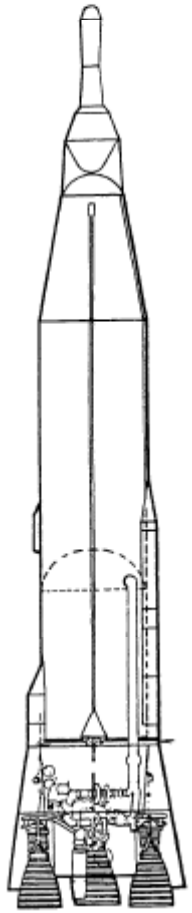
Systems Analysis - Trade-Offs



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**.

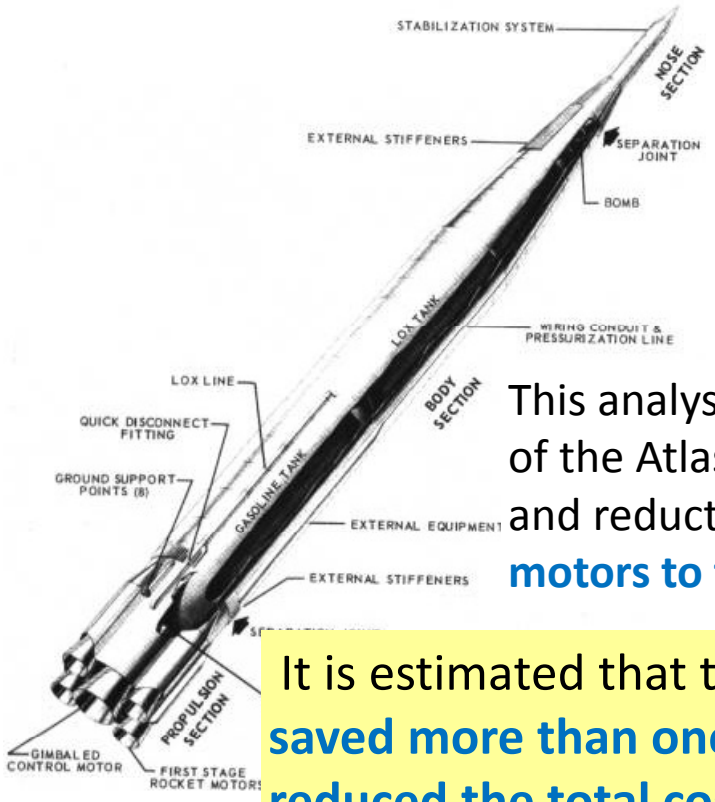


"Necessity as the Mother of Convention: Developing the ICBM, 1954-1958", Davis Dyer, BUSINESS AND ECONOMIC HISTORY, Fall 1993

What, How?

Systems Engineering to the rescue

Systems Analysis - Trade-Offs

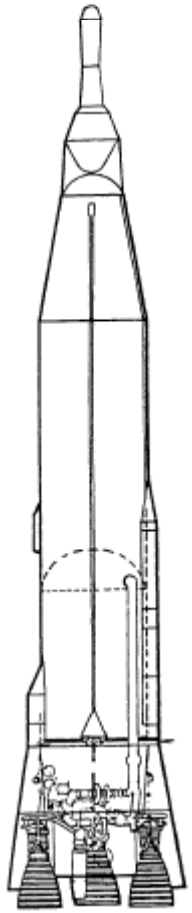


Nose-cone systems study

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**.



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

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

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

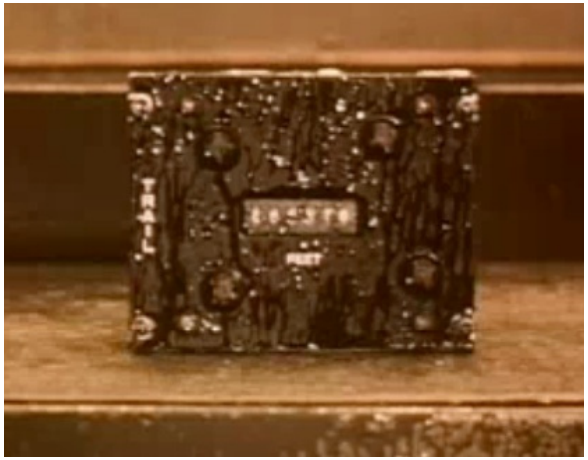
What, How?

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



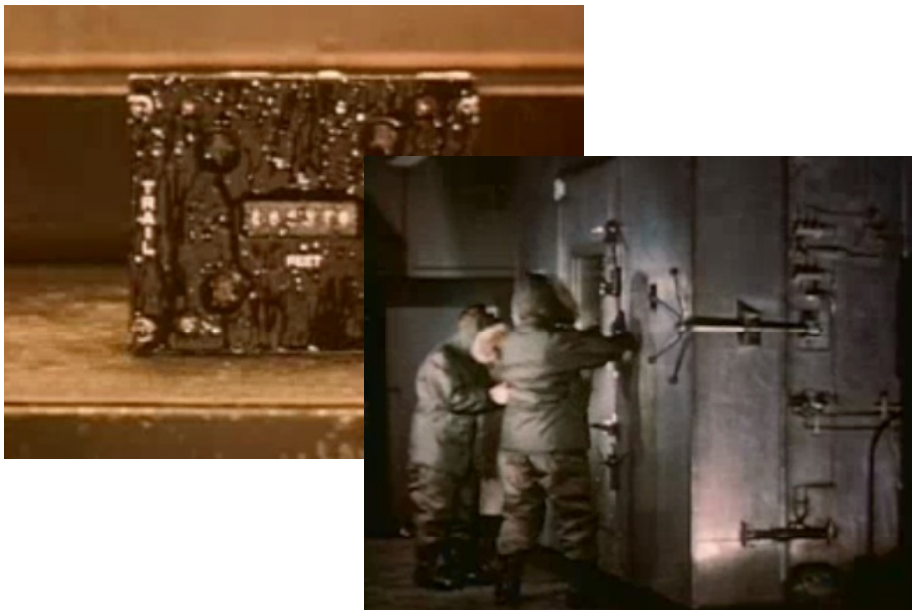
"On Guard! The Story of SAGE", IBM Corporation, Military Products Division, (ca. 1956), The Internet Archive, Prelinger Archives

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



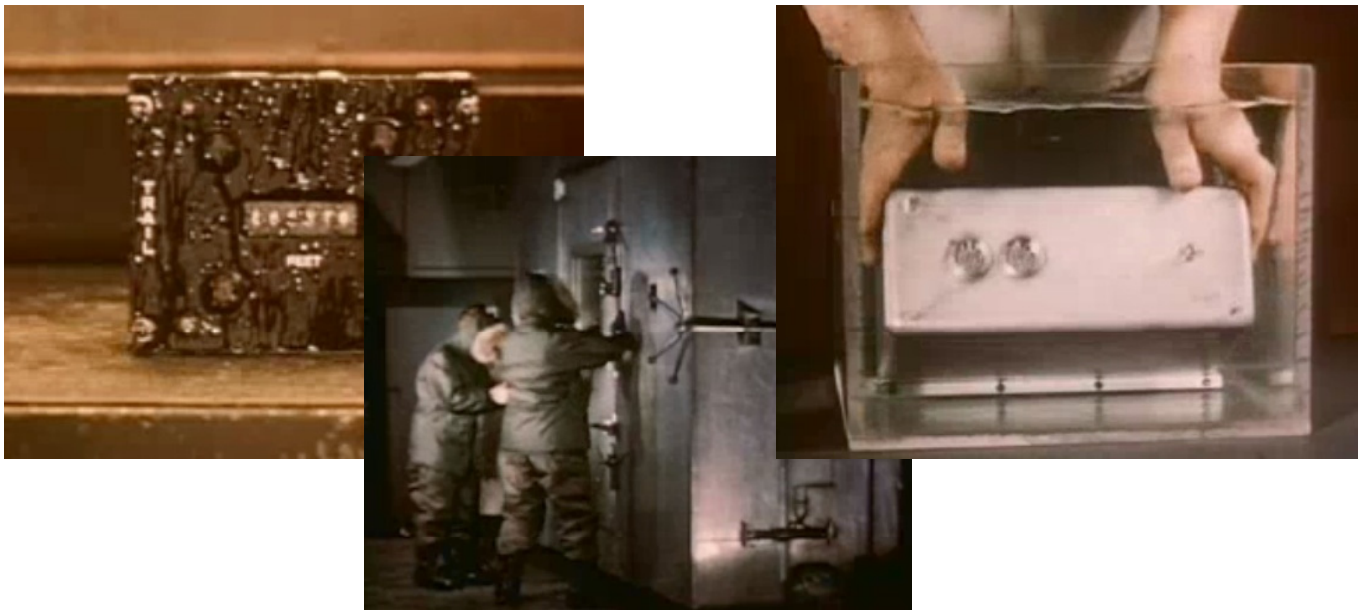
"On Guard! The Story of SAGE", IBM Corporation, Military Products Division, (ca. 1956), The Internet Archive, Prelinger Archives

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



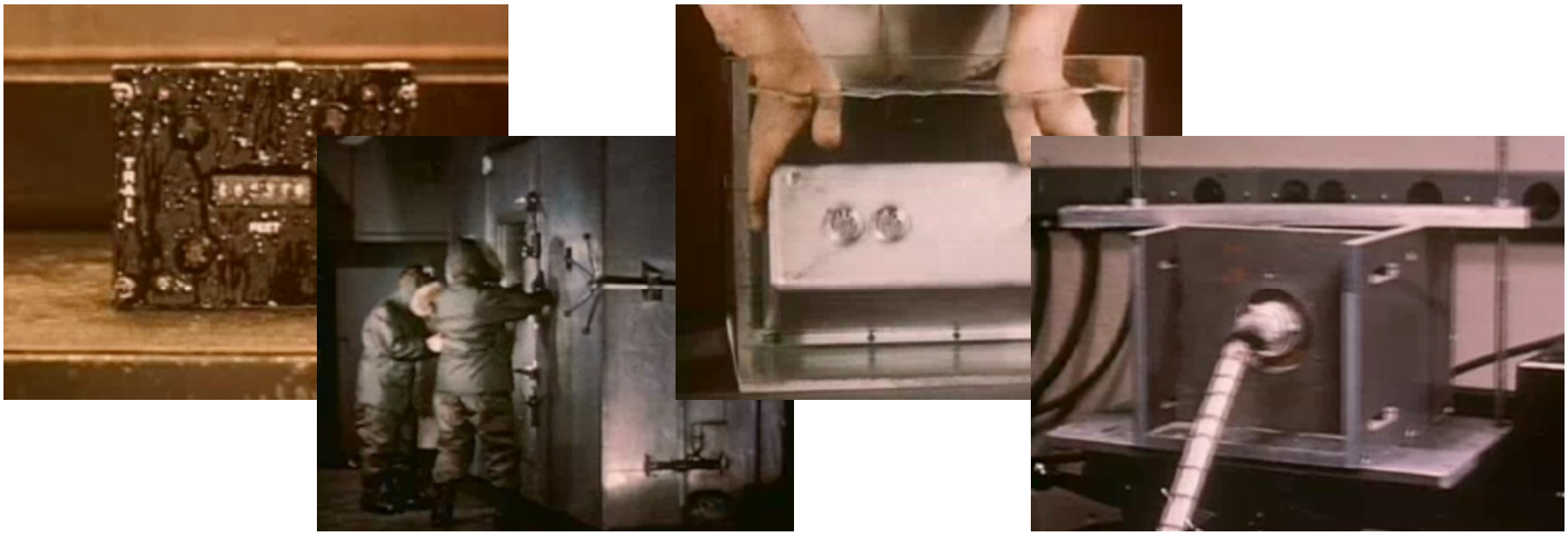
"On Guard! The Story of SAGE", IBM Corporation, Military Products Division, (ca. 1956), The Internet Archive, Prelinger Archives

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



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

What, How?

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

What, How?

Systems Engineering to the rescue

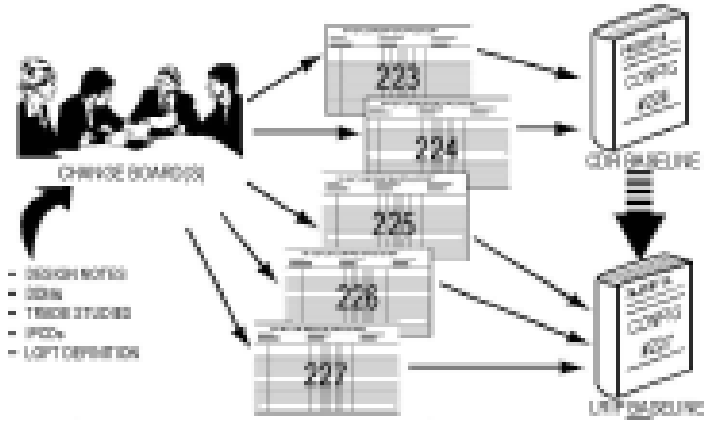
Change Control - Configuration Management

"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



What, How?

Systems Engineering to the rescue

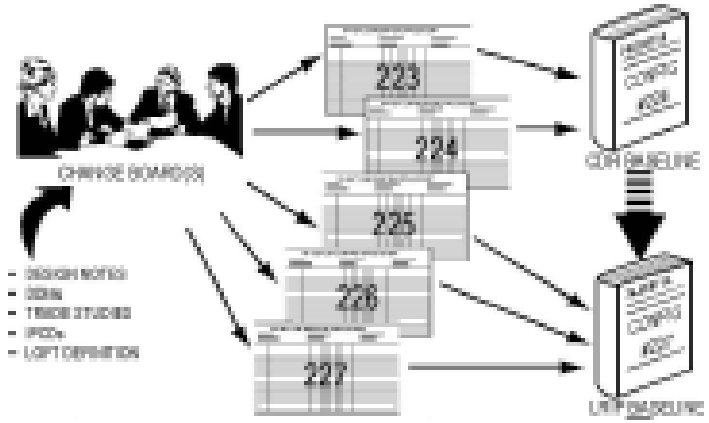
Change Control - Configuration Management

"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

What, How?

Systems Engineering to the rescue

System Management

What, How?

Systems Engineering to the rescue

System Management

A meeting in the program control and status room in the Air Force Ballistic Missile Division offices.
The United States Air Force and the Culture of Innovation, 1945–1965 - Stephen B. Johnson, Air Force History and Museums Program, Washington, D. C., 2002

What, How?

Systems Engineering to the rescue

System Management

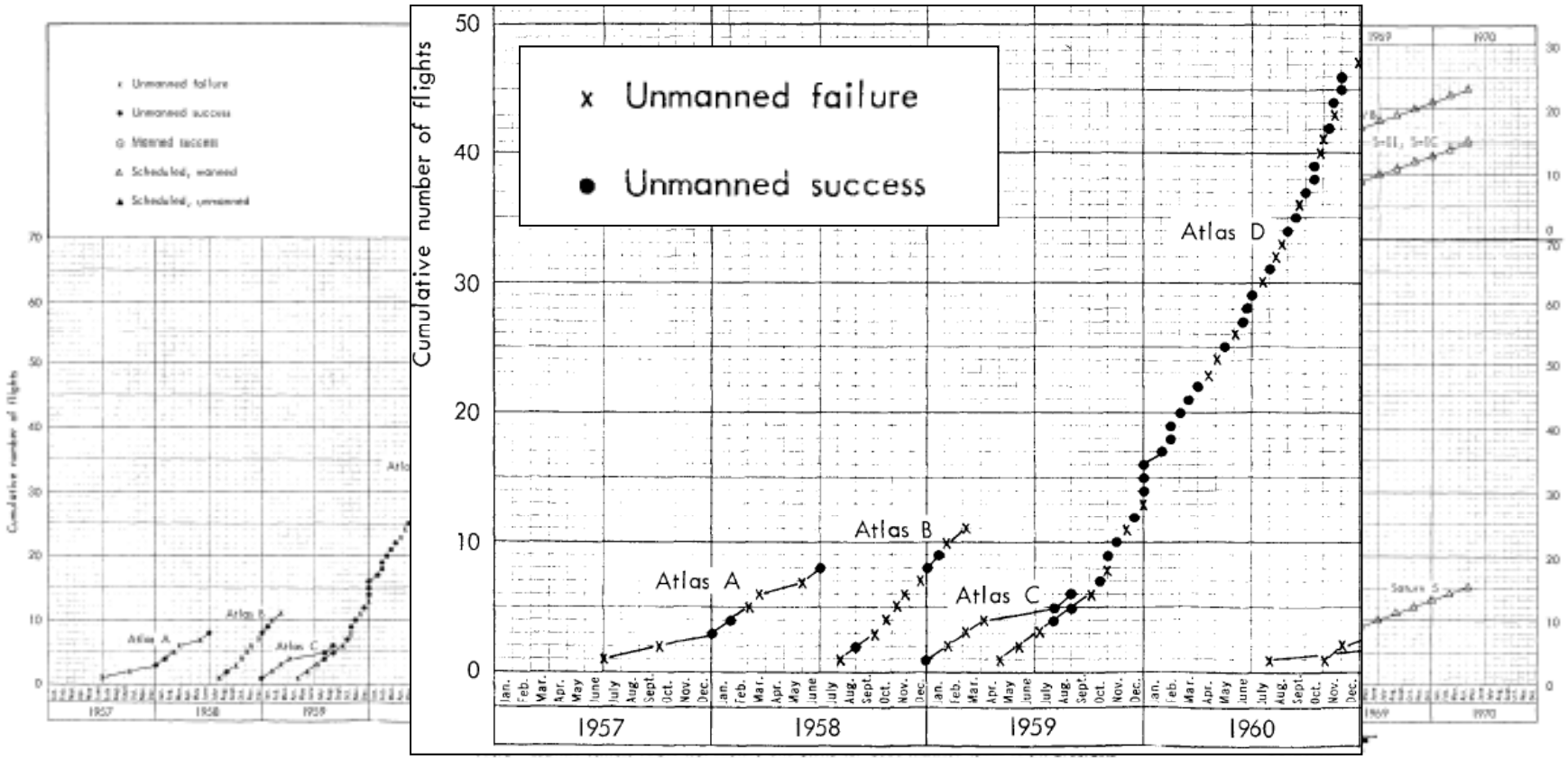
A meeting in the program control and status room in the Air Force Ballistic Missile Division offices.
The United States Air Force and the Culture of Innovation, 1945–1965 - Stephen B. Johnson, Air Force History and Museums Program, Washington, D. C., 2002

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

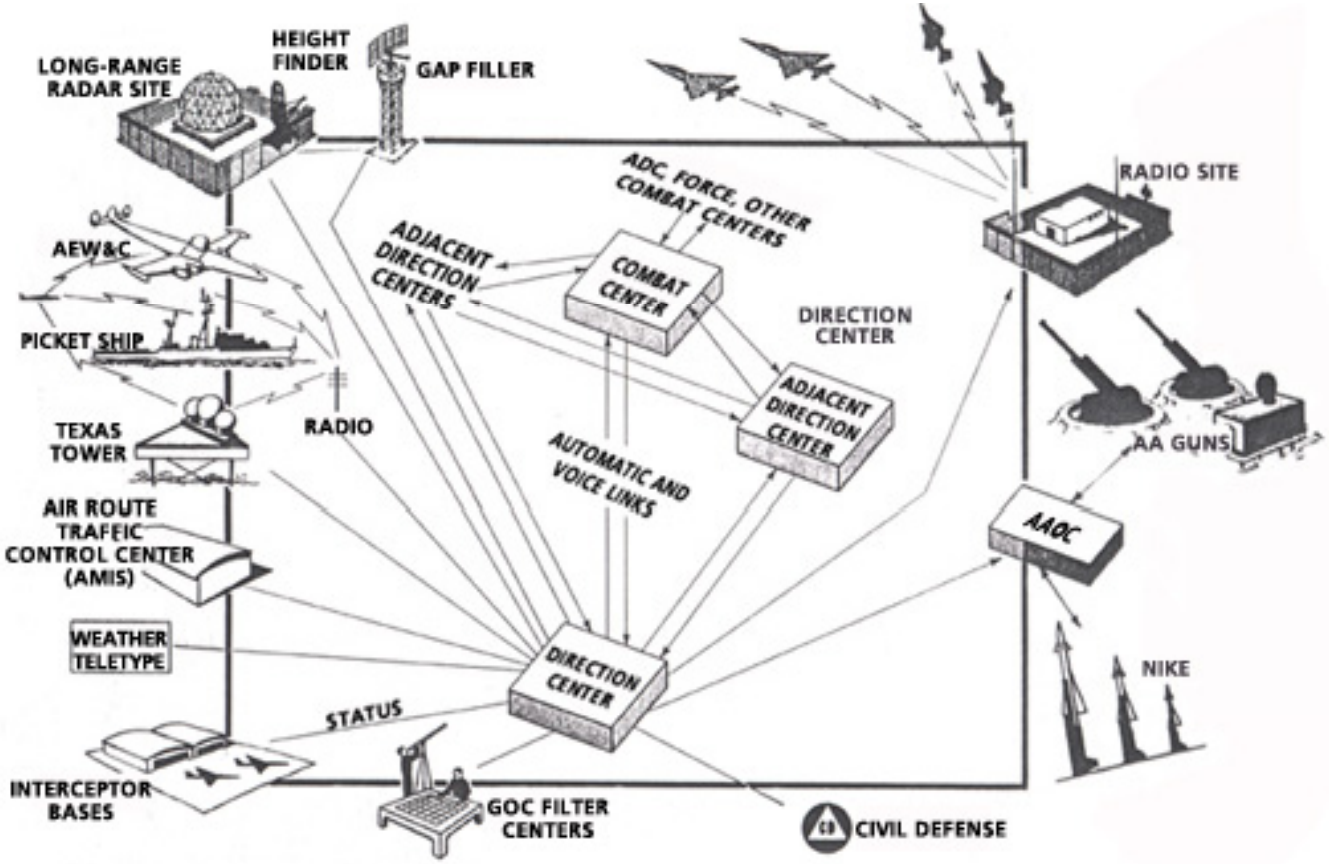


Apollo launch-vehicle man-rating: Some considerations and an alternative contingency plan - RAND Corporation, 1965

Semi-Automatic Ground Environment (SAGE)

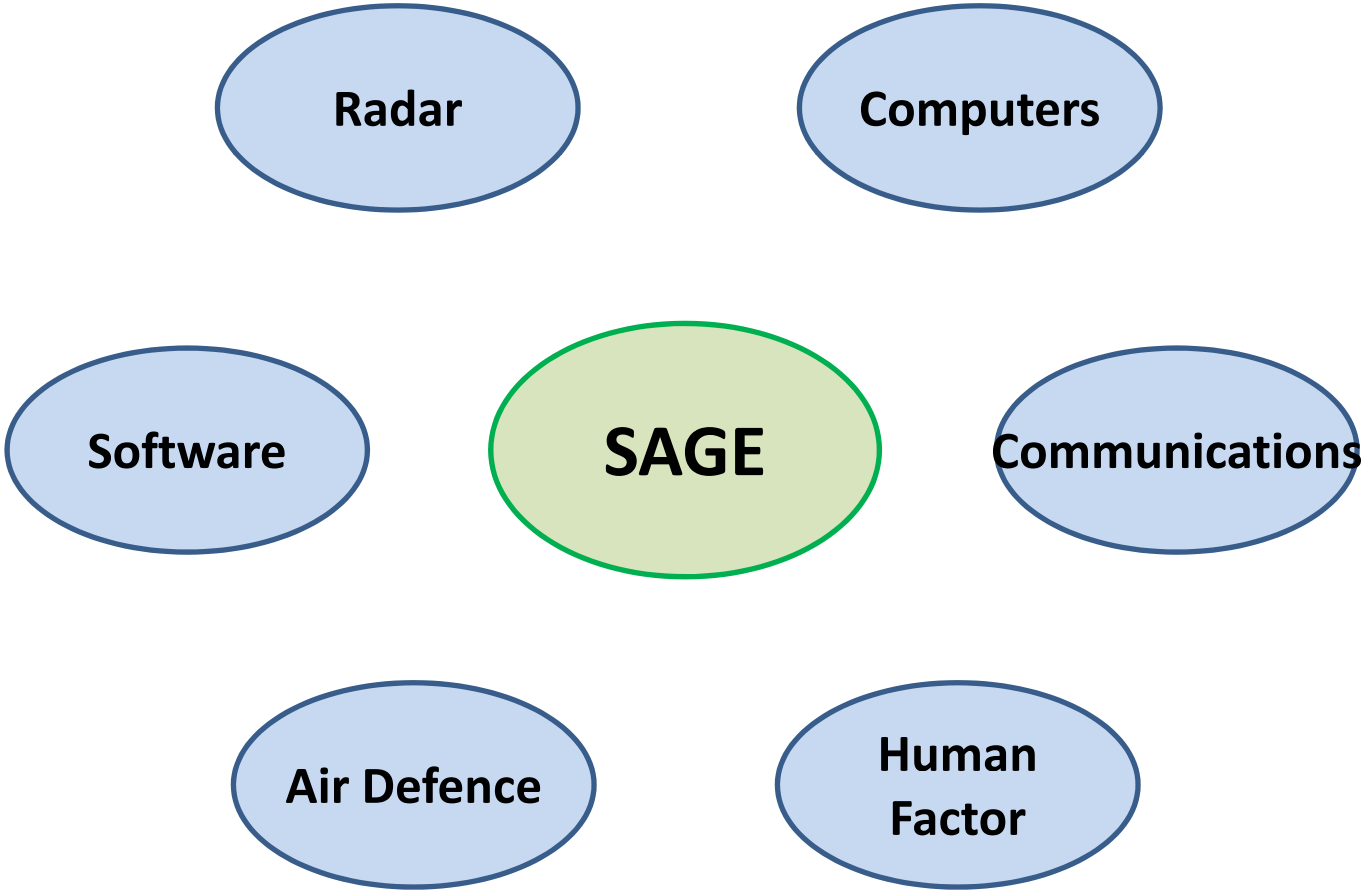
"**first major real-time, computer-based command-and-control system**.
Designed to protect the United States from long range bombers "

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



Why?

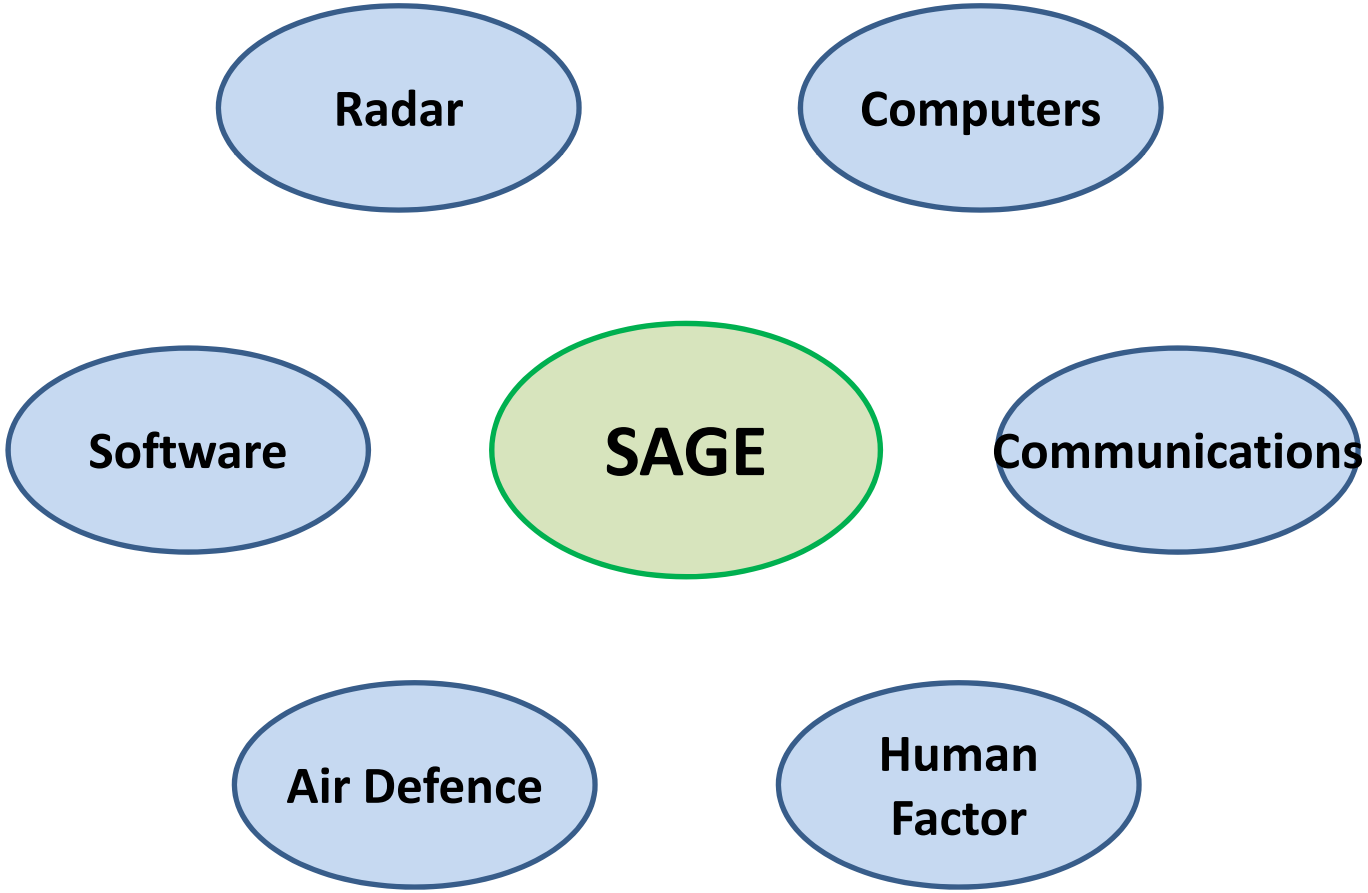
Multiple Technologies



Why?

Multiple Technologies

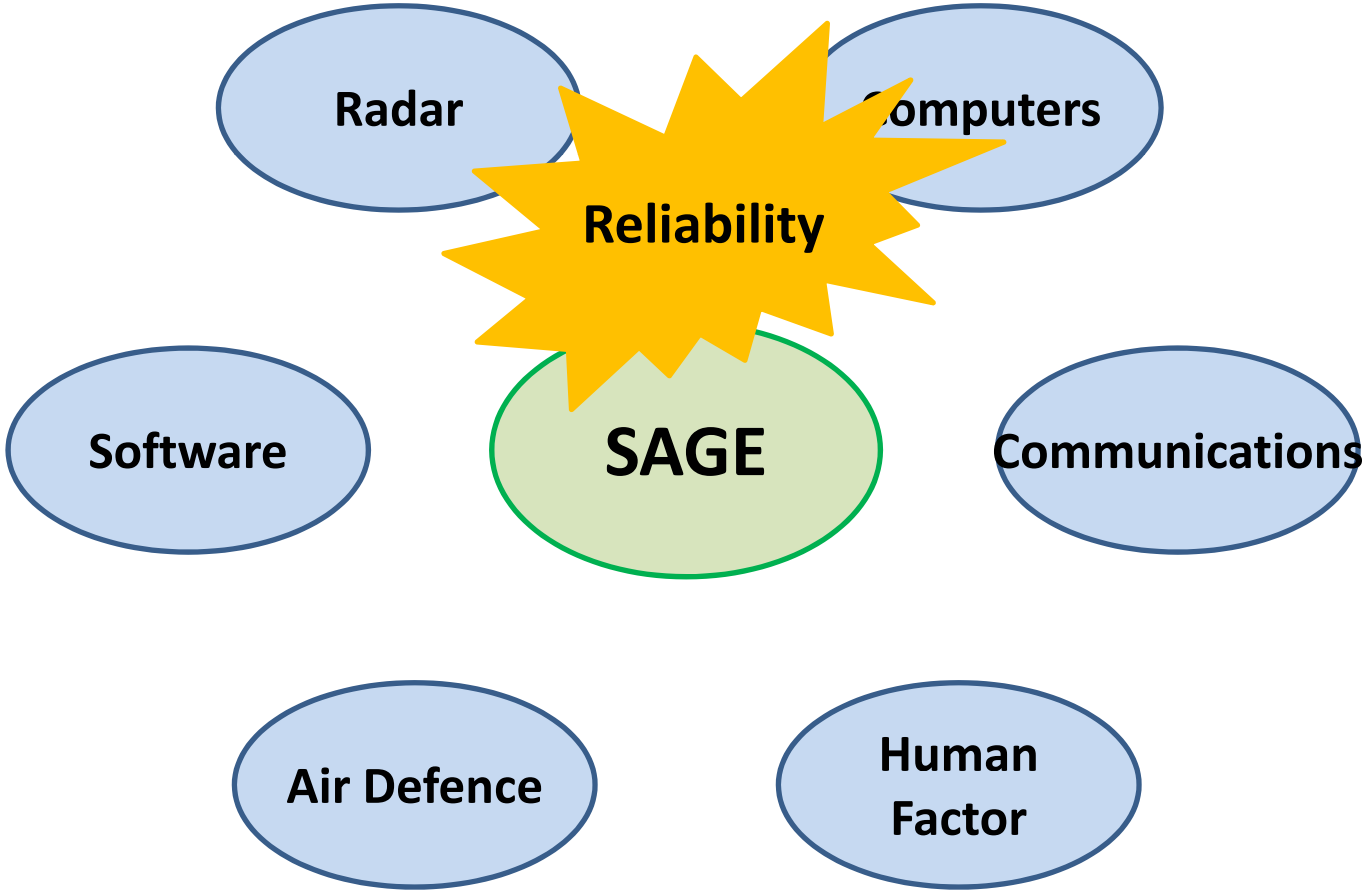
UNPRECEDENTED CHALLENGES



Why?

Multiple Technologies

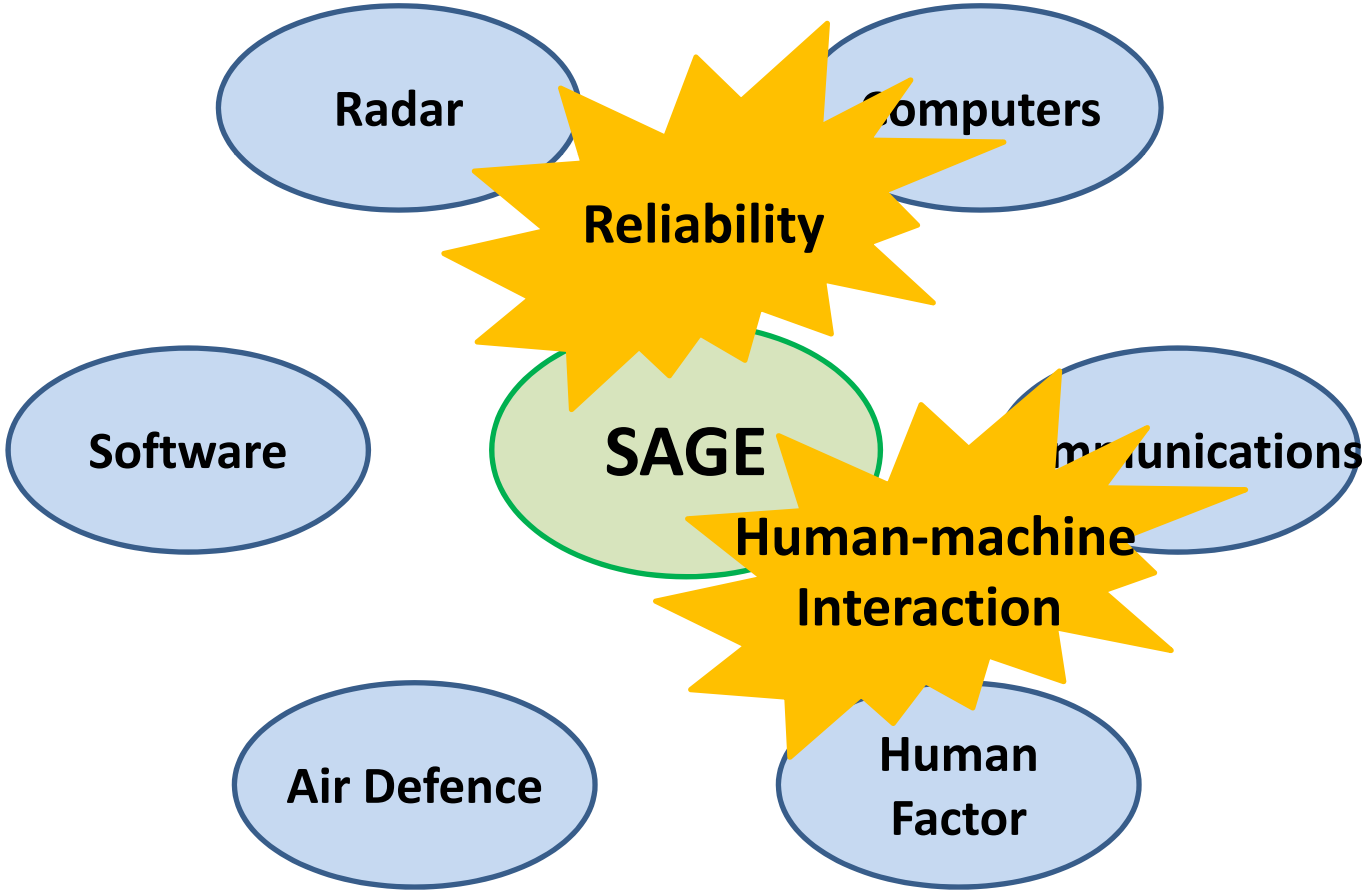
UNPRECEDENTED CHALLENGES



Why?

Multiple Technologies

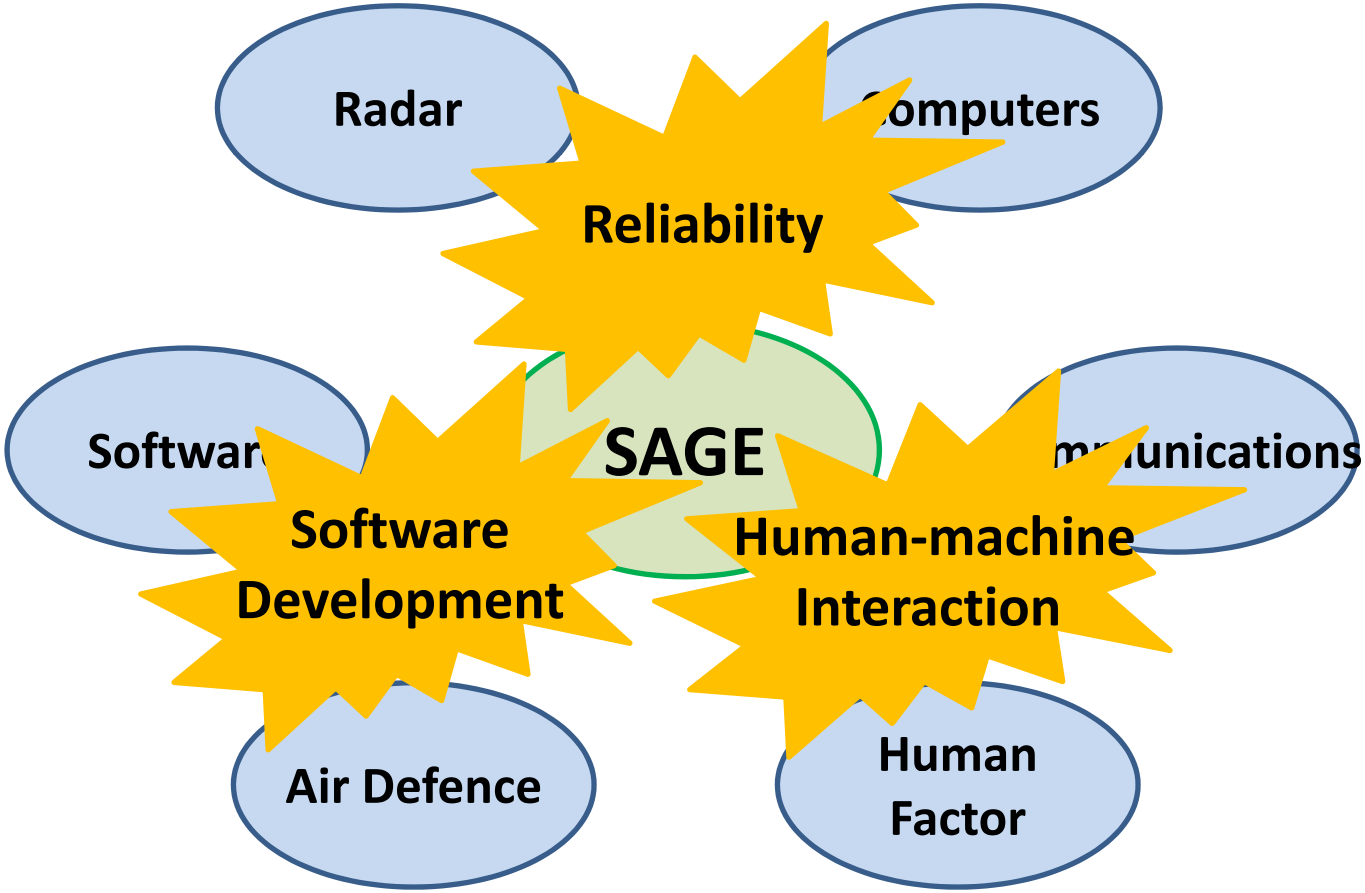
UNPRECEDENTED CHALLENGES



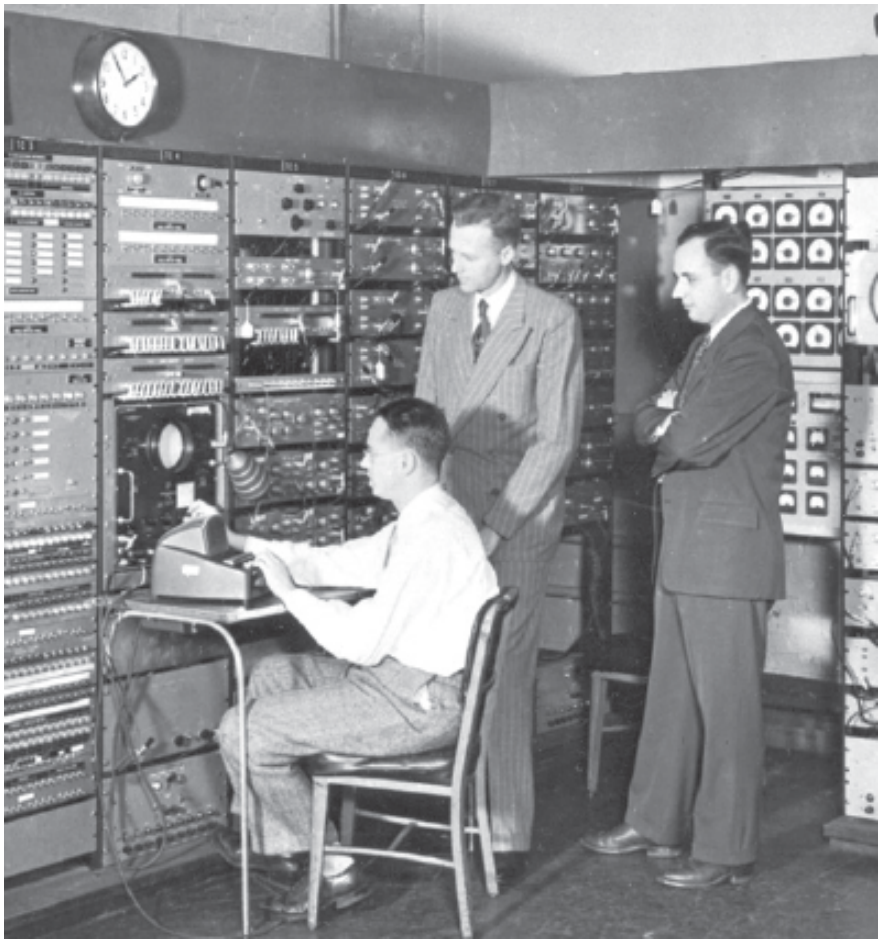
Why?

Multiple Technologies

UNPRECEDENTED CHALLENGES

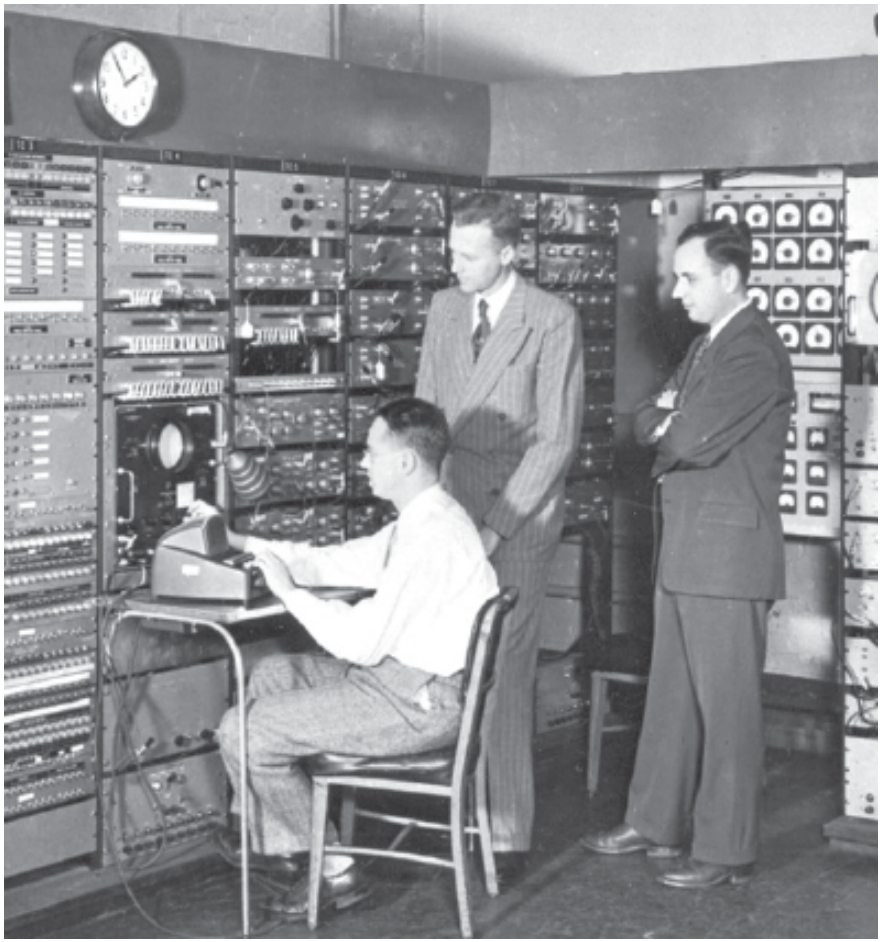


Who, Where?



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

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)

What, How?

Systems Engineering to the rescue

Reliability (systemic approach)

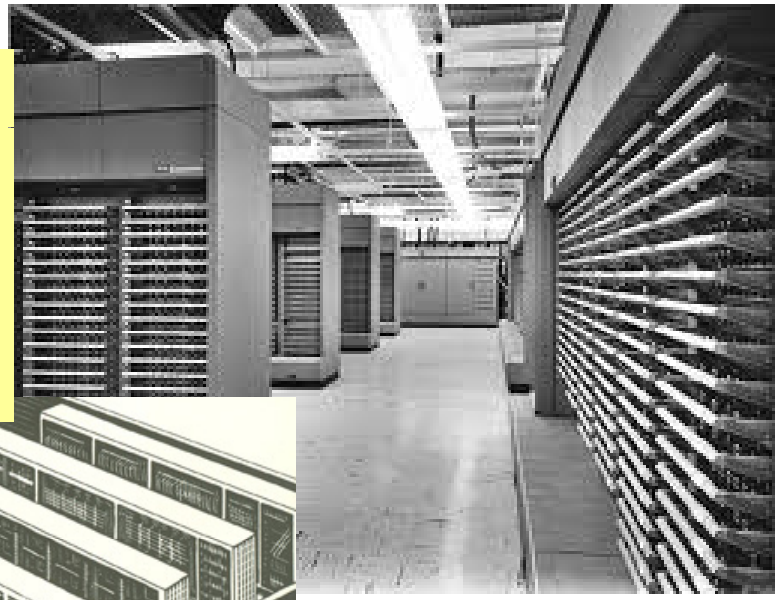
- **Vacuum Tube Life**
- **Marginal Checking**

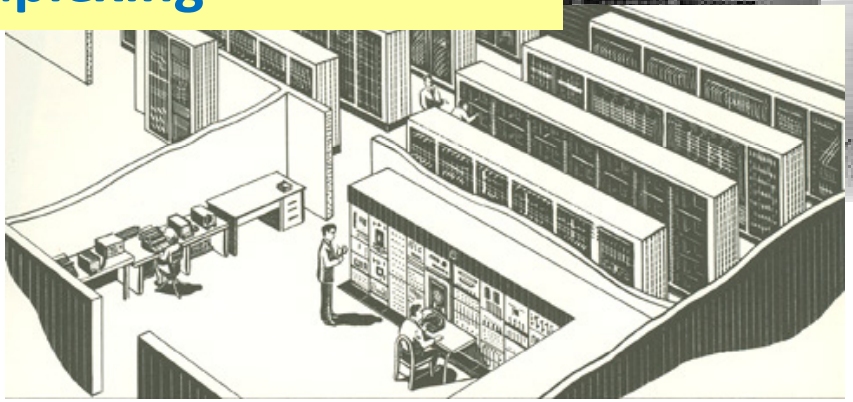
What, How?

Systems Engineering to the rescue

Reliability (systemic approach)

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



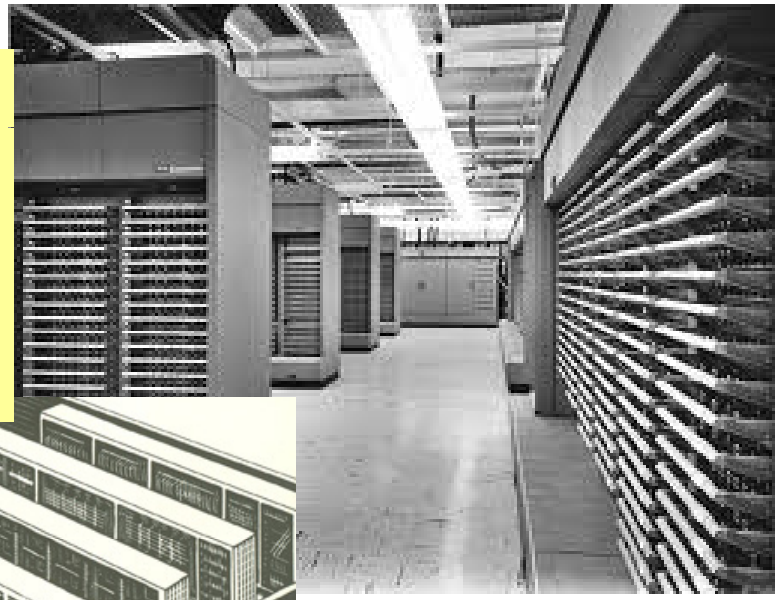


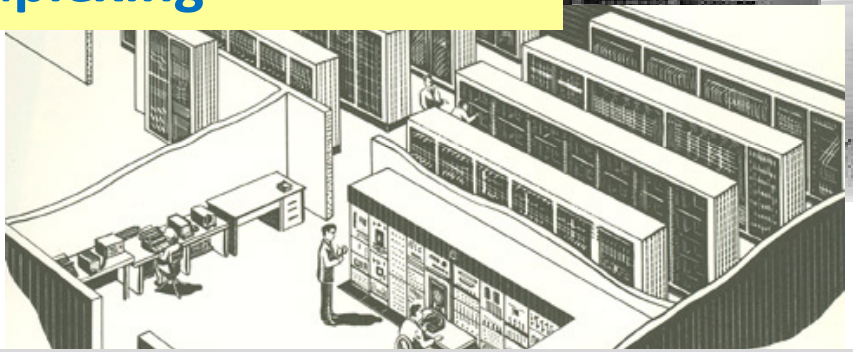
What, How?

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

What, How?

Systems Engineering to the rescue

Human System Integration

What, How?

Systems Engineering to the rescue

Human System Integration

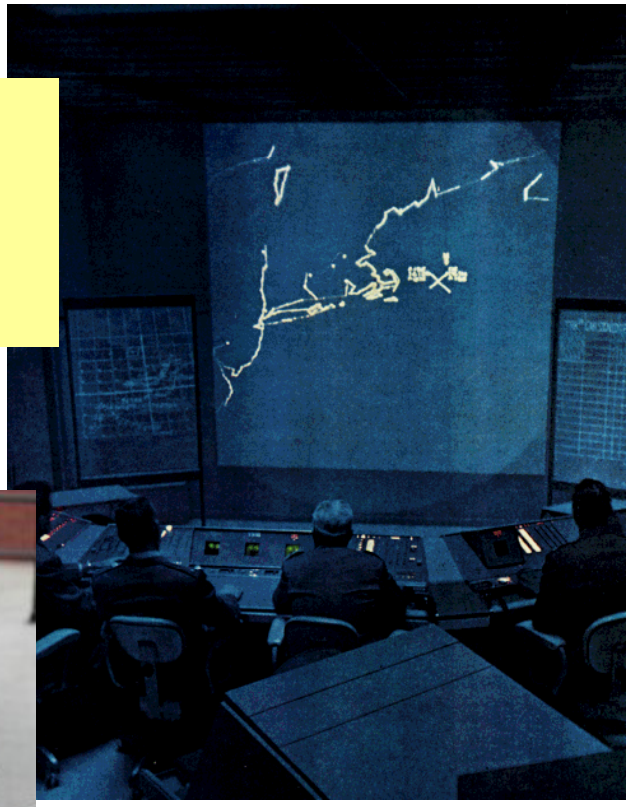
- **interactive graphic displays,**

What, How?

Systems Engineering to the rescue

Human System Integration

- interactive graphic displays,
- light-pen input

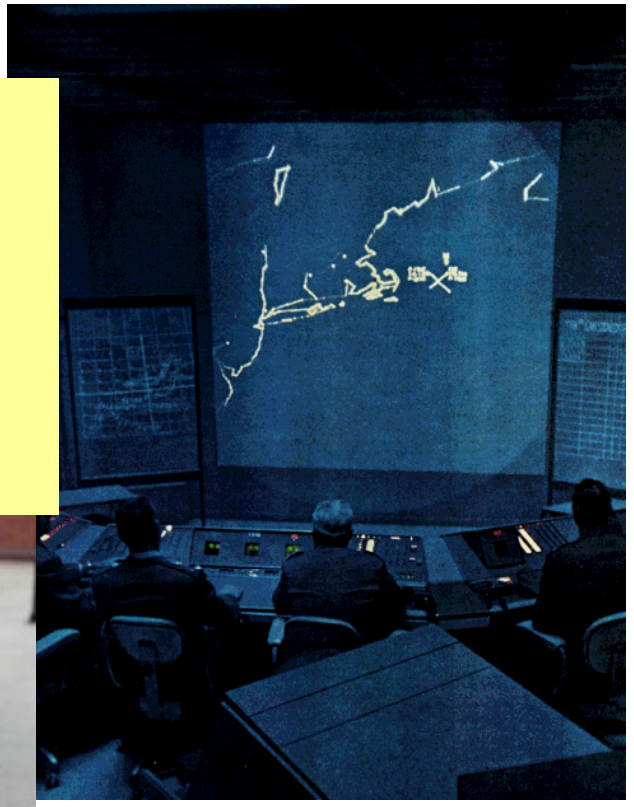


What, How?

Systems Engineering to the rescue

Human System Integration

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



What, How?

Systems Engineering to the rescue

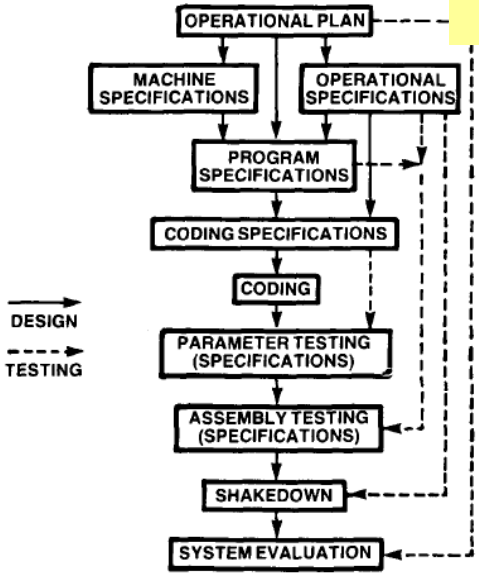
Software Development (method and documentation)

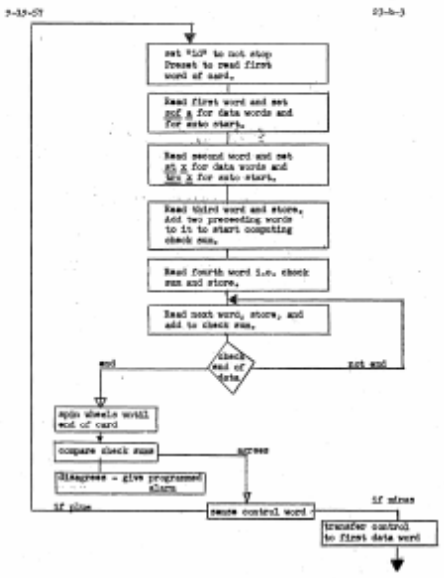
What, How?

Systems Engineering to the rescue

Software Development (method and documentation)

- process and documentation





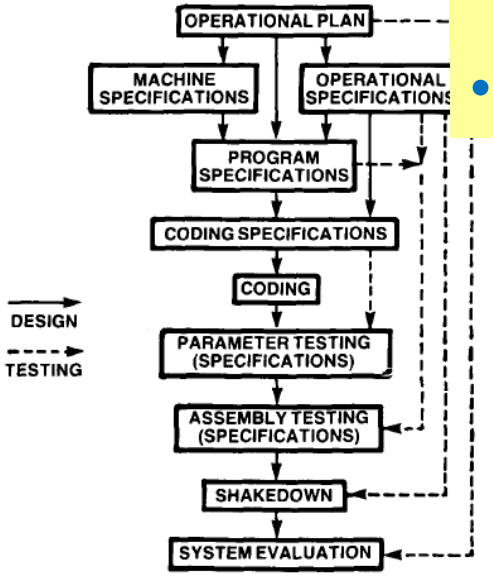
Production of Large Computer Programs - H. D. Bennington [1956], IEEE Annals of The History of Computing, 1983

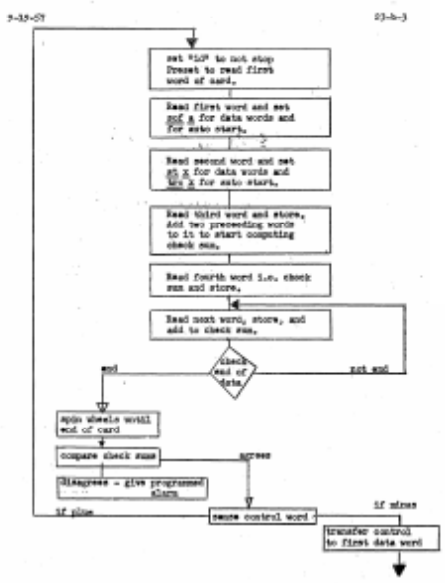
What, How?

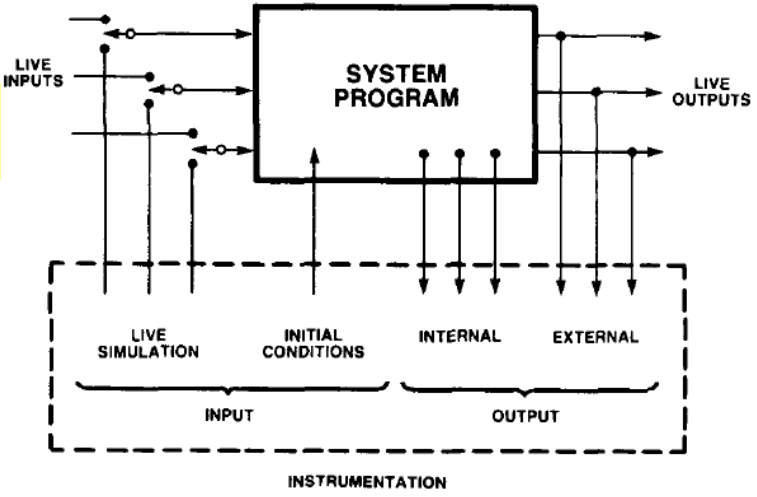
Systems Engineering to the rescue

Software Development (method and documentation)

- process and documentation
- thorough testing







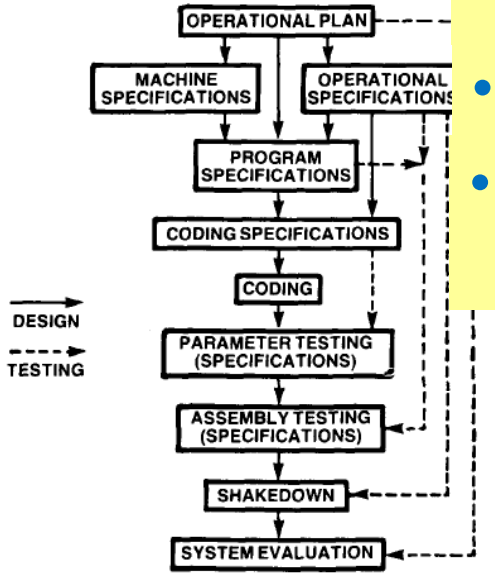
Production of Large Computer Programs - H. D. Bennington [1956], IEEE Annals of The History of Computing, 1983

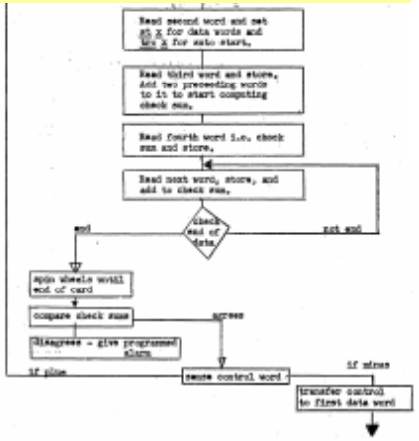
What, How?

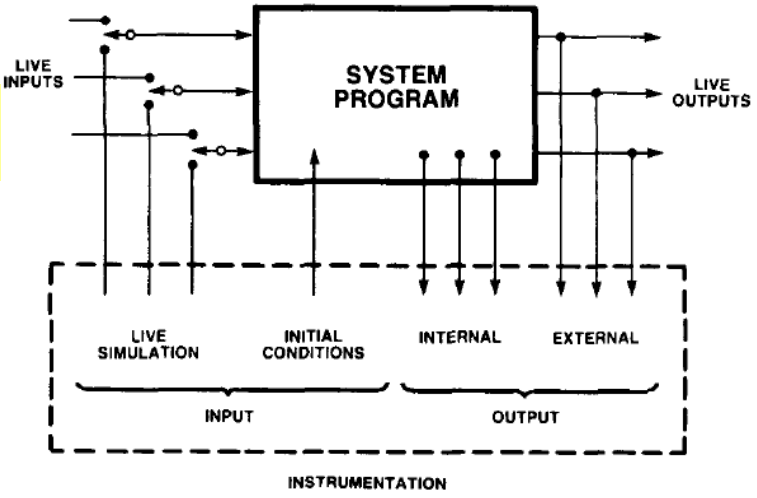
Systems Engineering to the rescue

Software Development (method and documentation)

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







Production of Large Computer Programs - H. D. Bennington [1956], IEEE Annals of The History of Computing, 1983

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

Systems Engineering **reaching maturity**

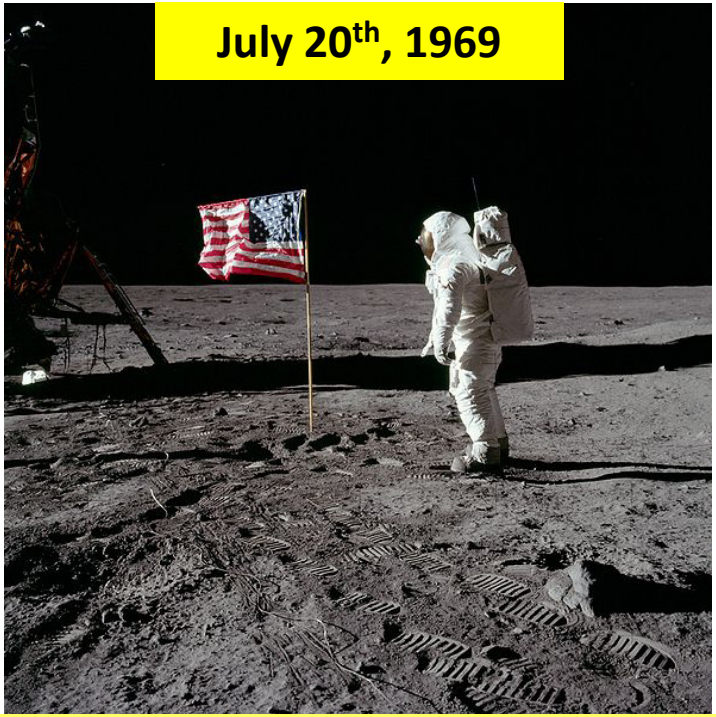
APOLLO Program

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 20th, 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

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

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**?

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

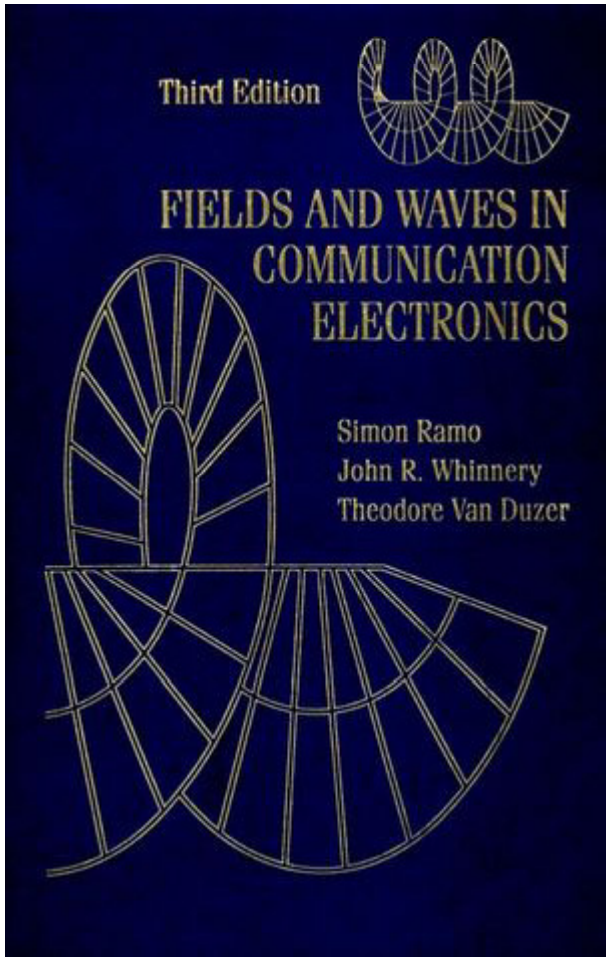
The winning trait of Systems Engineering

In an historical perspective, the capability, shown by Systems Engineering, to ***bring to success large complex projects*** (in, or before, time, and within budget), can be reasonably attributed to the **combination of awesome scientific and technical excellence with sensible and effective processes**.

Who?

Simon Ramo

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

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.

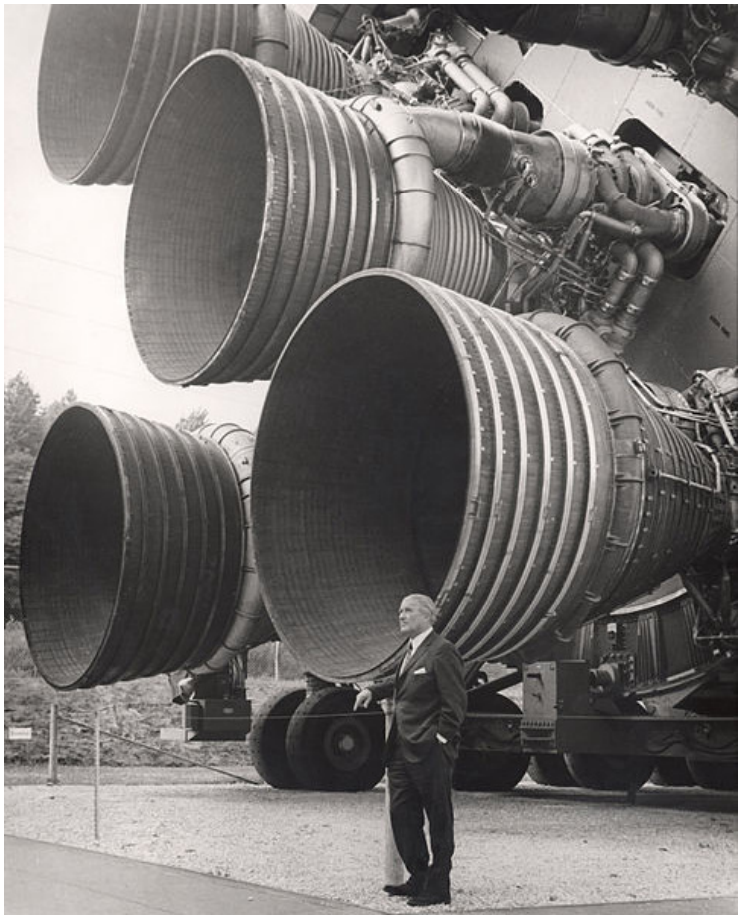
Forrester is the *Professor Emeritus of Management* in System Dynamics at the MIT Sloan School of Management.

http://mitsloan.mit.edu/faculty/detail.php?in_spseqno=41467

Who?

Wernher von Braun

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

Thank you for yor attention.

Questions?