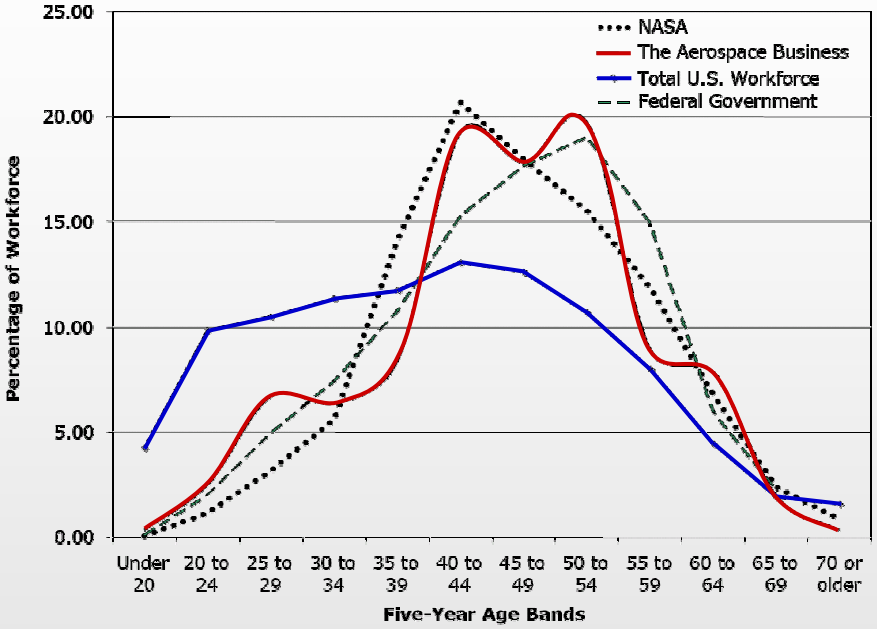
Collaborative Systems Thinking:

Towards an understanding of team-level systems thinking

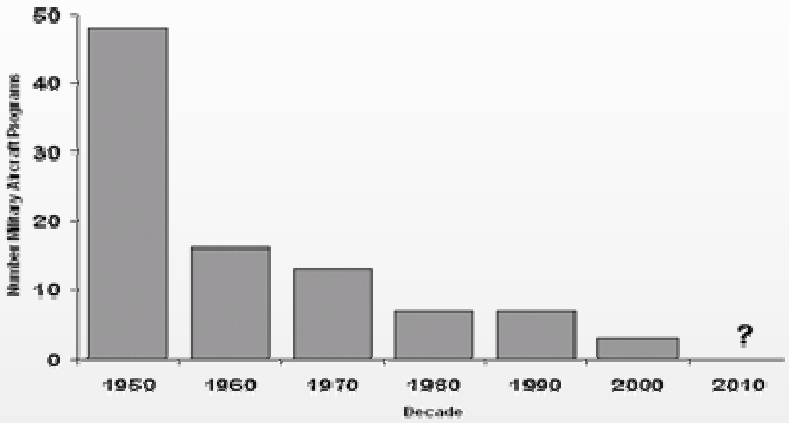
Caroline Twomey Lamb (presenting)
Deborah J. Nightingale and Donna H. Rhodes

6th Conference on Systems Engineering Research
April 4-5, 2008

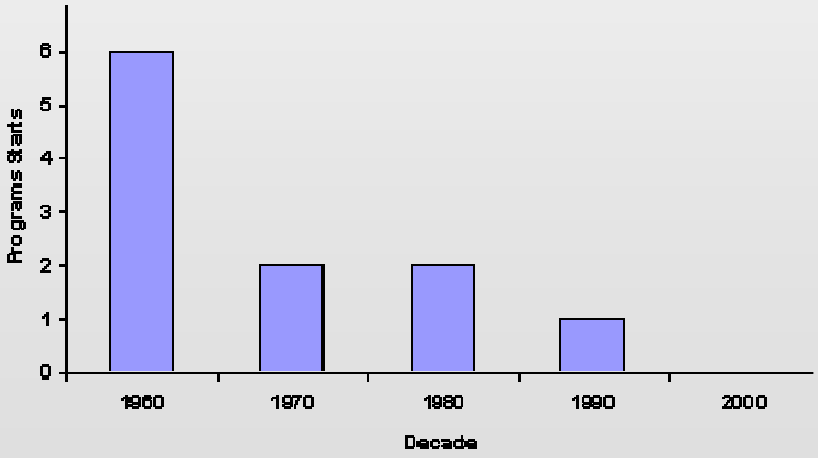
Aerospace Industry is Facing a Skills Crisis



Engineering Demographics in the US
(Future US Space Workforce 2005)



Manned Fighter Program Starts by Decade (Murman et al 2002)



Manned Spacecraft Program Starts by Decade (Neal 1995)

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R. Stephens. Ensuring Aerospace Skills of the Future. In Proc. AIAA/ICAS International Air and Space Symposium and Exposition: The Next 100 Years, Dayton, OH, August 2003.

V. Neal, C. Lewis, and F. Winter. Spaceflight. Macmillan, New York, NY, 1995.

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Importance of Teams for Systems Thinking

- Engineering is socio-technical activity
- Teams leverage breadth and depth of member experience
  - Portfolio approach
  - Multiple thinking styles
  - Experience on different programs
  - Different areas of expertise
- Teams regarded as better for safety-critical decisions (Salas and Fiore 2004)

Logistical Complexity	Physical Complexity	Design Space Complexity
– Social coordination – Maintaining awareness of 'whole' – Managing interfaces – Realizing opportunities at interfaces	– Large number of components – Static: component compatibility – Dynamic: emergence	– Exploration of design space – Requirements negotiation – Identification of 'sweet spots' within design space

E. Salas and S. Fiore. Why team Cognition? An overview. In E. Salas and S. Fiore, editors, Team Cognition, chapter 1, pp 11-32. American Psychological Association, Washington, DC, 2004.

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Exploring Team-Level Systems Thinking

Research Questions

- What are the empirically generalized traits of systems thinking teams?
- What aspects of team culture and technical process usage correlate with team-level systems thinking?

Research Objectives

1. An operational definition characterizing team-level systems thinking
2. A set of heuristics for enabling collaborative systems thinking
3. Descriptive theory of collaborative systems thinking
4. Potential influences
   - Workforce development
   - Technical process tailoring
   - Enterprise architecture

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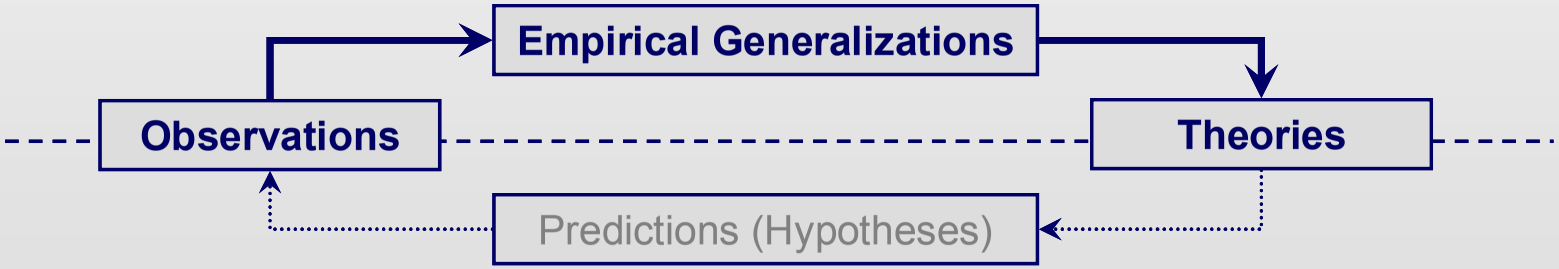
Research Context

- MIT Systems Engineering in the Enterprise
  - Enablers and Barriers to Systems Thinking Development (Davidz 2006, Davidz 2008)
  - Collaborative Distributed Systems Engineering (Utter 2007)
- Collecting empirical data for systems engineering theory (Valerdi and Davidz 2007)
  - Case Studies (Yin 2003)
  - Grounded Theory methods (Strauss and Corbin 1998)
    - **Description:** Use of words to describe a mental image of a person, experience, etc.
    - **Conceptual ordering:** Organization of data according to pertinent dimensions and properties
    - **Theory building:** A set of related concepts within a relational framework suitable for explaining the observed behavior



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D. Utter. Collaborative Distributed Systems Engineering, Master of Science Thesis, Engineering Systems Division, MIT, January 2007.

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Research Format

- Phase 1: Literature Review
  - Define what is team-level systems thinking
  - Establish framework for further inquiry
- Phase 2: Pilot Interviews
  - Validation of research directions
- Phase 3: Case Studies
  - Empirical data
  - Basis for theory development

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Phase 1: What is Systems Thinking?

A framework for systems with four basic ideas: emergence, hierarchy, communication and control. Human activity concerns all four elements. Natural and designed systems are dominated by emergence. (Checkland 1999)

A method of placing the systems in its context and observing its role within the whole. (Gharajedaghi 1999)

A skill to see the world as a complex system and understanding its interconnectedness. (Sterman 2000)

A skill of thinking in terms of holism rather than reductionism. (Ackoff 2004)

A method and framework for describing and understanding the interrelationships and forces that shape system behavior. (Senge 2006)

R. Ackoff. Transforming the Systems Movement. Opening Speech at 3rd International Conference on Systems Thinking in Management, May 2004. Philadelphia, PA.

P. Checkland. *Systems Thinking, Systems Practice, Soft Systems Methodology: A 30-year retrospective*. John Wiley and Sons, West Sussex, England, 1999.

J. Gharajedaghi. *Systems Thinking: Managing chaos and complexity*. Butterworth-Heinemann, Burlington, MA, 1999.

P. Senge. *The Fifth Discipline*. Doubleday, New York, NY, 2006.

J. Sterman. *Business Dynamics: Systems thinking and modeling for a complex world*. McGraw-Hill, New York, NY, 2000.

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Phase 1: Systems Thinking within Engineering

*Systems thinking is utilizing modal elements to consider the **componential**, **relational**, **contextual**, and **dynamic elements** of the **system** of interest.*

(Davidz 2006)

- Divergence in definition among engineers, engineering organizations
- Common themes for enabling systems thinking development (Davidz 2008)
  - Experiential learning
  - Individual characteristics
  - Supportive environment

H. Davidz. Enabling Systems Thinking to Accelerate the Development of Senior Systems Engineers. PhD thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, 2006.
H. Davidz. Enabling Systems Thinking to Accelerate the Development of Senior Systems Engineers. Systems Engineering. Vol. 11 No. 1

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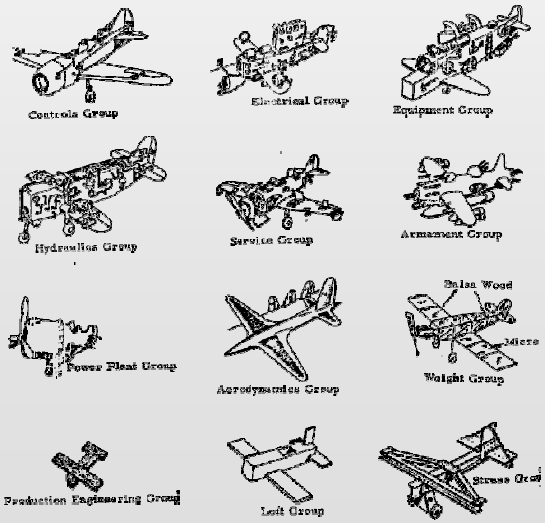
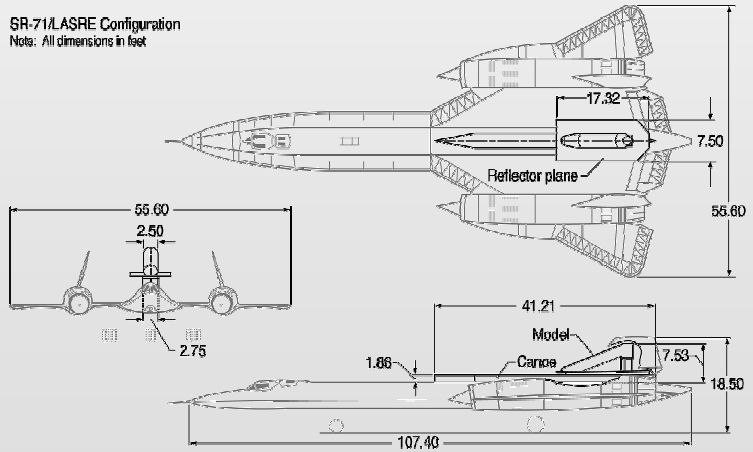
Phase 1: Collaborative Systems Thinking

Collaborative systems thinking is an emergent behavior of teams resulting from the interactions of team members and utilizing a variety of thinking styles, design processes, tools and communication media to consider the system, its components, interrelationships, context, and dynamics toward executing systems design (Lamb, 2008)



"Dream Airplanes" by C. W. Miller



C. Lamb Systems Thinking as an Emergent Team Property. IEEE Systems Conference, Toronto, Canada, April 2008

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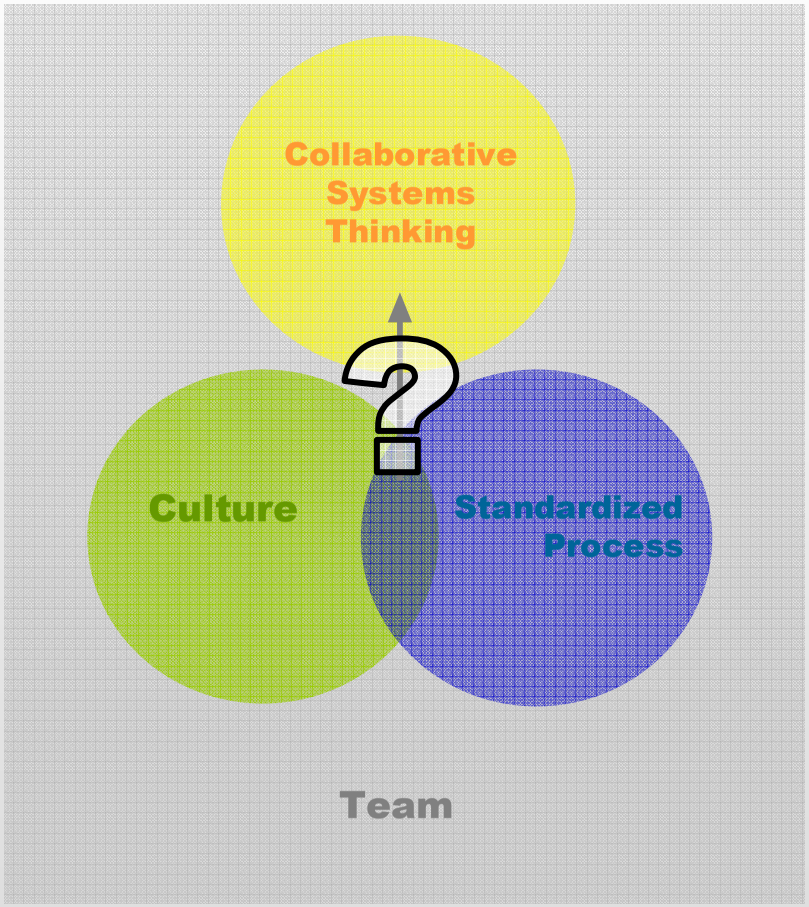
Phase 1: Conceptual Framework



Organizational Culture	Standardized Technical Process
Team norms	Documented tasks and methods
Espoused beliefs	Vision statements
Underlying assumptions	Strategy for standardization
Social networks	Process flow maps, org-charts

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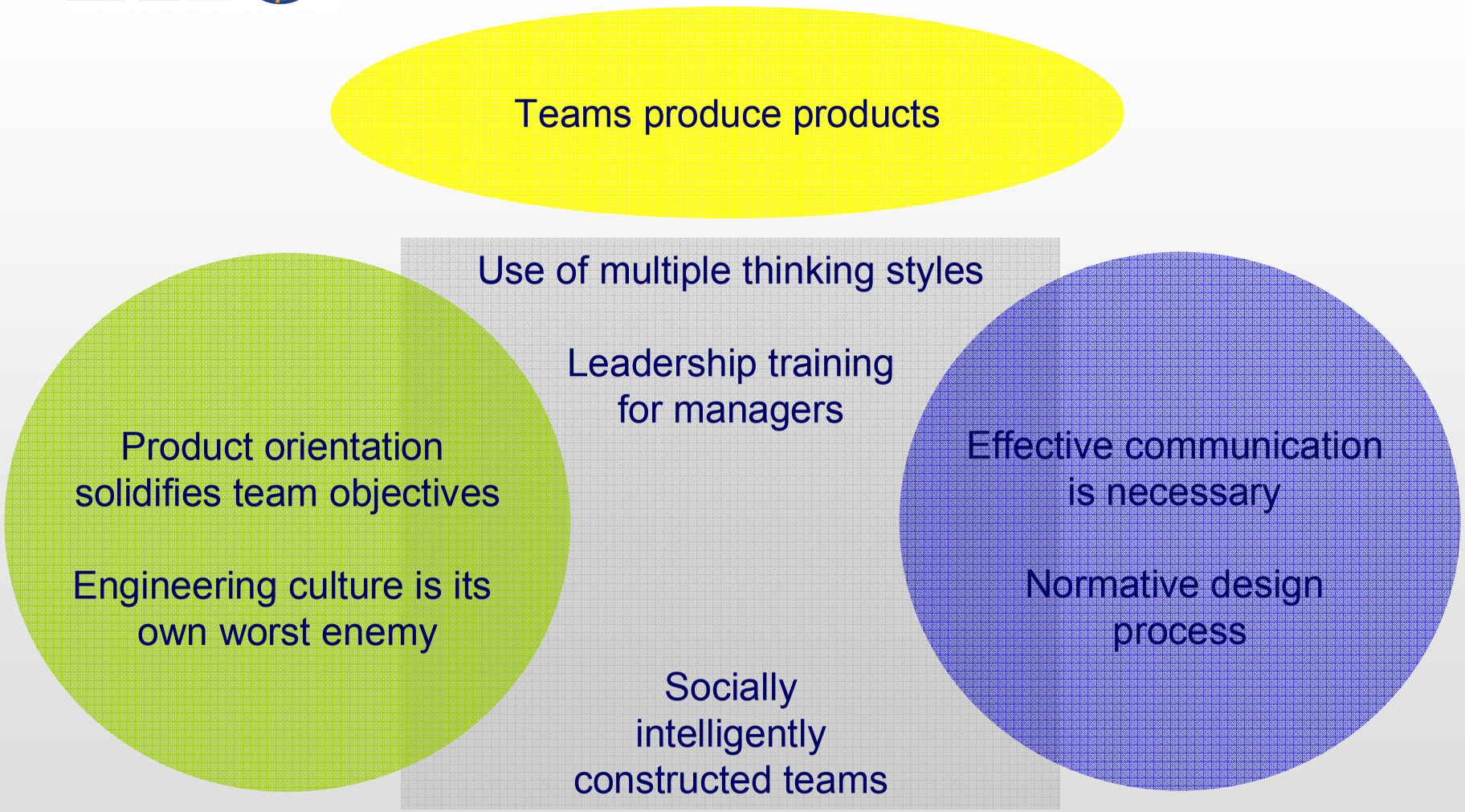
Phase 2: Pilot Interviews



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Phase 3: Case Studies

Collaborative Systems Thinking to be evaluated through 1st and 3rd person assessments

i. Self perception of systems thinking
ii. 3rd party report of systems thinking
iii. Blue chip panel
iv. Team effectiveness—metrics of performance

1) Teams that engage in multiple thinking styles are better systems thinkers

i. Education: degree, concentration
ii. Evidence of convergent/ divergent
iii. Multiple M-B types

2) Teams with more experience are better systems thinkers

i. Education: degree
ii. Time together
iii. Training
iv. Individual member past experience

Team-level systems thinking, collaborative systems thinking, is influenced by team culture and technical process

3) Teams with individual systems thinkers are more likely to engage in systems thinking

i. Self perception of systems thinking
ii. Understanding of role within system
iii. Understanding of role within process

5) Teams that engage in analysis before evaluation are better systems thinkers

i. Normative design process
ii. Open questioning
iii. Creative environment

4) Team work environment is an important enabler to systems thinking

i. Strong sense of team
ii. Ability to critically analyze ideas independent of individuals
iii. Individual sense of contribution
iv. Mutual respect and trust
v. Communication

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Phase 3: Next Steps

- Case Study Procedures
  - Day 1
    - Introduce myself and research
    - Team survey
  - Day 2
    - Interviews with team members
  - Day 3
    - Manager/supervisor interviews

- Goal of 15-20 cases
- Concentration on aerospace industry
- Theoretical sampling methods based on 5 variables

Independent Variables					Dependent Variable
Customer	Industry Sector	Program Lifecycle	Process Maturity	Team Size	Collaborative Systems Thinking
US Gov.	Aircraft (Hardware)	Conceptual Design	High	<10	Strong
Commercial	Spacecraft (Hardware)	Detail Design	Low	>10	Weak
Private					

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Interested in sponsoring a case study?

Email cmtwomey@mit.edu for more information

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Backup Slides

Back up to systems thinking slides
Importance of Systems Thinking

Aerospace systems are complex

Logistical Complexity	•Systems broken into hierarchy of smaller components •Need to maintain awareness of whole •Complex interfaces •Leverage opportunities at interfaces •Complexity in inter- and intra- team interactions
Physical Complexity	•Large number of components •Static complexity: pieces fitting together •Dynamic complexity: Interactions, emergent behavior
Design Space Complexity	•Exploration of design space •Maneuver requirements •Identification of 'sweet spots' within design space

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Team, Standard Process & Culture

Team

D. Ancona, H. Bresman, and K. Kaeufer. The Comparative Advantage of X-Teams. *MIT Sloan Management Review*, 43(3):33-39, 2002.

R. Belbin. *Team Roles at Work*. Elsevier, London, 1993.

R. Newman. Issues in Defining Human Roles and Interactions in Systems. *Systems Engineering*, 2(3):143-155, 1999.

E. Salas and S. Fiore. Why *team* Cognition? An overview. In E. Salas and S. Fiore, editors, *Team Cognition*, chapter 1, pages 11-32. American Psychological Association, Washington, DC, 2004.

Culture

R. Belie. Non-Technical Barriers to Multidisciplinary Optimization in the Aerospace Community. In *Proc. 9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimization*, Atlanta, GA, September 2002.

E. Schein. *Organizational Culture and Leadership*. Jossey-Bass, San Francisco, CA, 2004.

Process

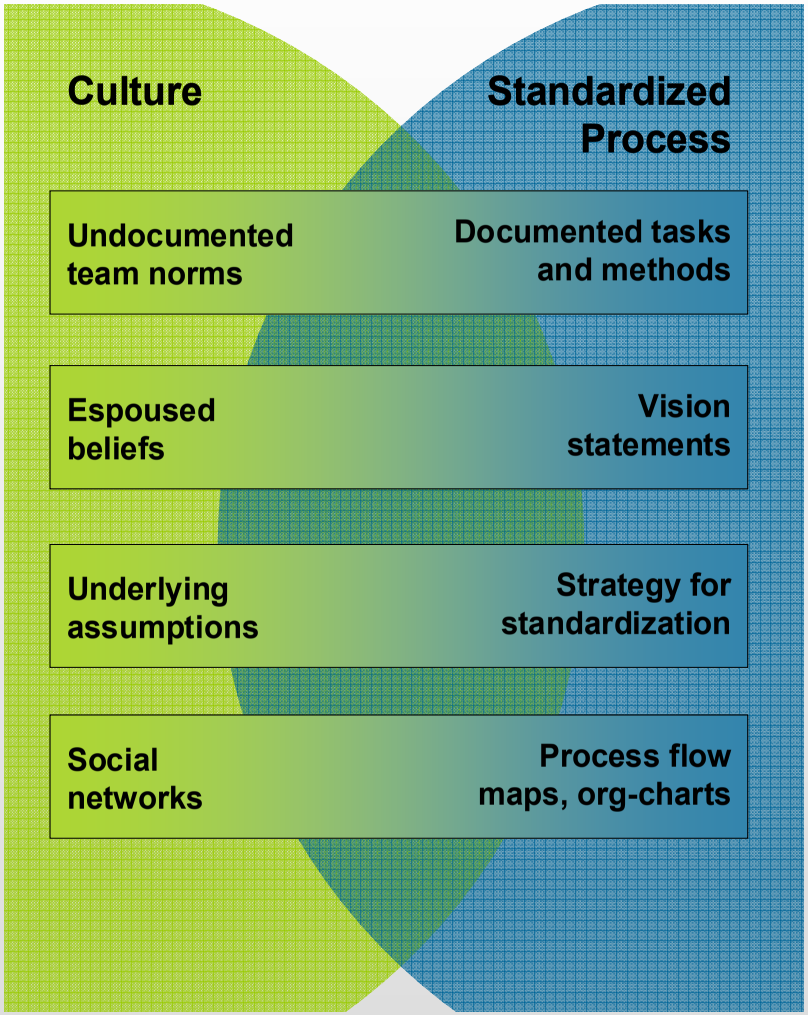
J. Martin. *Systems Engineering Guidebook*. CRC Press, Boca Raton, FL, 1997.

D. Rhodes. Frequently Asked Questions on Systems Engineering Process. In *Proc. 4th INCOSE International Symposium*, San Jose, CA, 1994.

J. Stempfle and P. Badke-Schaub. Thinking in Design Teams: An analysis of team communication. *Design Studies*, 23(1):473-496, 2002.

Team

- Social systems
- Group of individuals
- Task interdependency
- Represent multiple backgrounds
  - Disciplines
  - Experience
- Great breadth of knowledge
- More reliable for safety critical decisions (Salas and Fiore 2004)



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Backup—Team

- Team: a co-acting group of individuals
  - Bring greater breadth of knowledge to problem
  - Teams are more reliable for making safety critical decisions (Salas and Fiore 2004)
- Benefits to bringing functions together early in design
  - Two-thirds lifecycle cost determined in conceptual design
  - Concurrent engineering and Integrated Product Teams (IPTs) reduce failures due to poor communication (Newman 1999)
- Many theories of team structures
  - X-Teams (Ancona 2002)
  - Team roles
    - Functional
    - Basic (Belbin 1993)

D. Ancona, H. Bresman, and K. Kaeufer. The Comparative Advantage of X-Teams. *MIT Sloan Management Review*, 43(3):33-39, 2002.
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Backup—Process

- Process: a logical sequence of tasks towards achieving an objective
  - Way to decompose a large task into smaller subtasks (Martin 1997)
  - Standardization way to reduce ambiguity, improve repeatability
- Concerned with technical processes
  - May be standardized at many levels
  - Facilitate collaboration (Rhodes 1994)
- Several theories of process design (Stempfle and Badke-Schaub 2002)
  - Normative design theory
    - Divergent-convergent
  - Natural (empirical) design theory
    - Convergent

J. Martin. *Systems Engineering Guidebook*. CRC Press, Boca Raton, FL, 1997.
D. Rhodes. Frequently Asked Questions on Systems Engineering Process. In *Proc. 4th INCOSE International Symposium*, San Jose, CA, 1994.
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Backup—Culture

- Culture: an abstraction for explaining group behavior (Schein 2004)
  - Artifacts and behavioral norms
  - Espoused Beliefs
  - Underlying Assumptions
- Culture can be a barrier to introduction of new methods, tools and processes (Belie 2002)
- Culture exists at several levels
  - Organizational culture
    - Beliefs and values held by an organization and its employees
    - Team variations in behaviors result in subcultures
  - Engineering culture
    - Beliefs and behaviors linked to profession
    - Consistent across organizations

R. Belie. Non-Technical Barriers to Multidisciplinary Optimization in the Aerospace Community. In *Proc. 9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimization*, Atlanta, GA, September 2002.
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Research Framework

- Four constructs to frame inquiry
  - Team
  - Standard Technical Process
  - Culture
    - Organizational culture
    - Engineering culture
    - Team norms and behavior
  - Collaborative systems thinking

Map to enablers from past research on systems thinking
- Individual Characteristics
- Experiential Learning
- Supportive Environment
- Systems thinking

- Use of Mixed Qualitative/Quantitative Research Methods
  - Techniques and tools borrowed from social science
  - Similar to past LAI, Aero-Astro, and ESD theses
  - Uses qualitative and quantitative data types to describe systems thinking within teams

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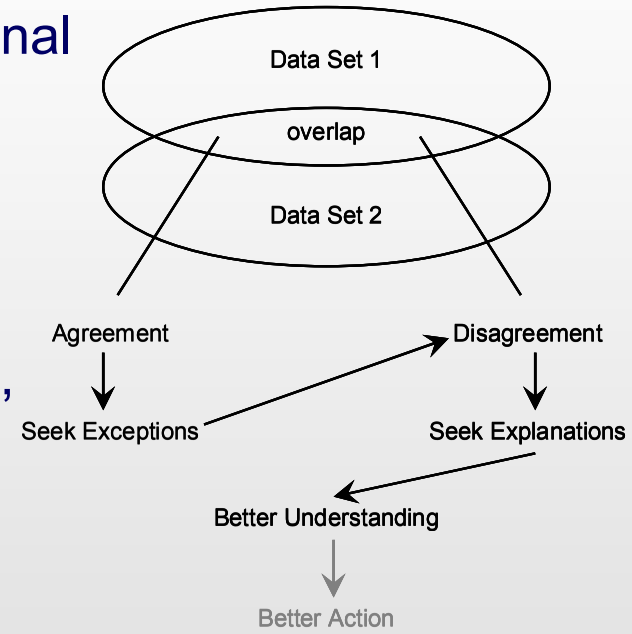
Qualitative Data Analysis

- Coding
  - Definition: breakdown of textual data into central ideas with goal of creating relational structure for interpreting data and explaining observations
  - Open, axial, and selective coding
- Memo writing
  - Definition: record of researcher thoughts, data interpretations and questions
  - Code, theoretical, operation, diagrams
- Tools
  - NUD*IST, NVivo 7
  - ESMs (?)



K. Eisenhardt. Building Theories from Case Study Research. *The Academy of Management Review*, 14(4):532{550, 1989.
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R. Stebbins. *Exploratory Research in the Social Sciences*, volume 48 of *Sage University Papers Series on Qualitative Research Methods*. Sage Publications, Thousand Oaks, CA, 2003.
A. Strauss and J. Corbin. *Basics of Qualitative Research: Techniques and procedures for developing grounded theory*. Sage Publications, Thousand Oaks, CA, 1998.

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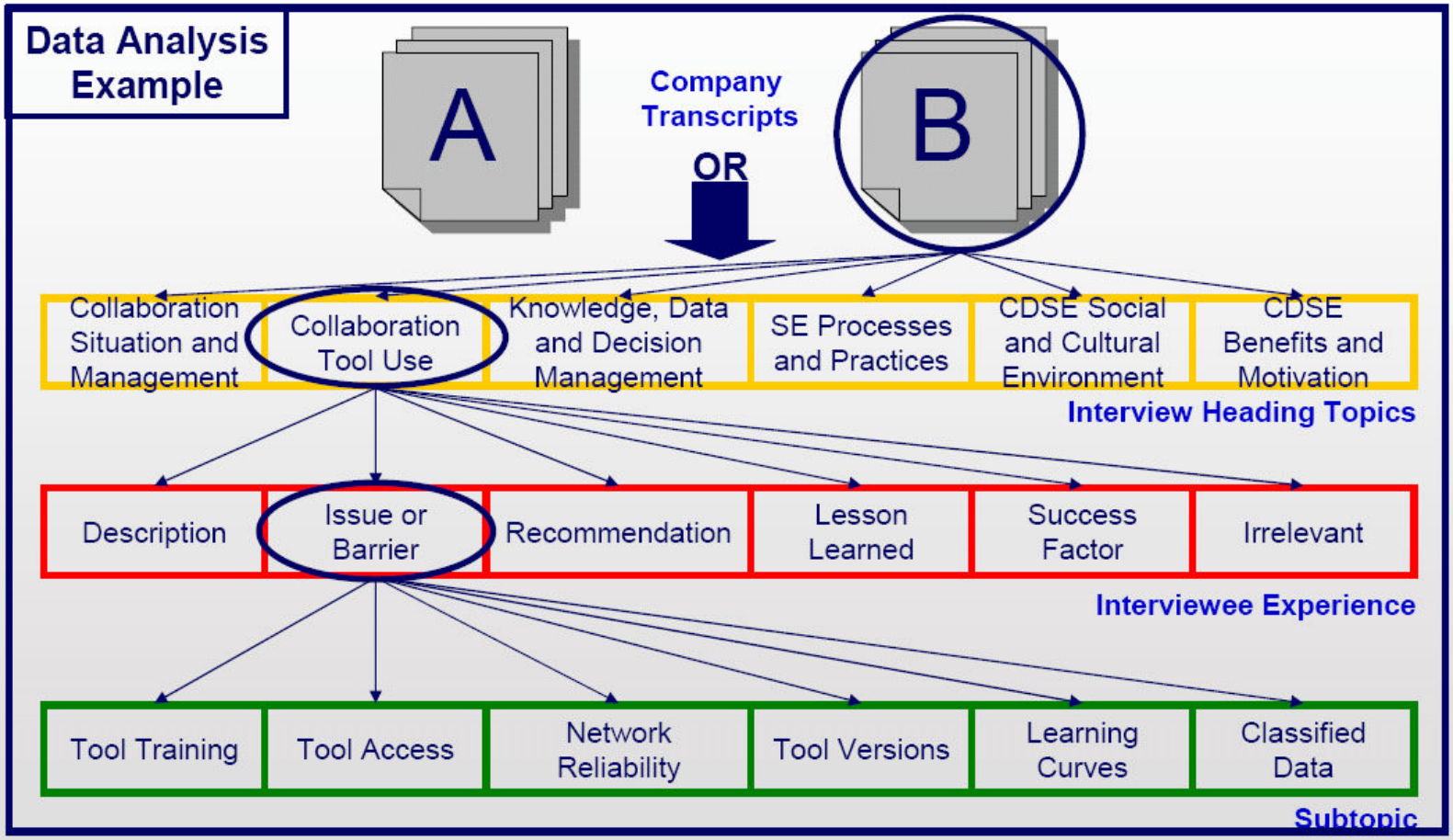
Qualitative Data Analysis: An Illustrative Example



Example of data coding and code hierarchy from similar research

D. Utter. *Collaborative Distributed Systems Engineering*, Master of Science Thesis, Engineering Systems Division, MIT, January 2007.

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Quantitative Analysis Candidates

Quantitative methods often used within grounded theory research

- Survey result reduction
  - Characterize mean response, spread in response
- Comparison of code frequencies between pre-identified groups (Davidz, 2006)
  - Chi-square tests: used to test statistical significance of difference between proportions for two or more groups
  - Potential use: identifying differences between teams, between groups of teams
- Test of construct validity (Edmondson, 1999)
  - Multitrait multimethod (MTMM) matrix
  - Test that measures for same construct more highly correlated than measures for other constructs
- Regression analysis
  - Examines relation of dependent variable (CST) to independent variables (team traits)
  - Measure contribution of different traits to presence/quality of CST
- Factor analysis
  - Statistical data reduction technique used to explain variability among observed (assumed random) variables in terms of fewer random unobserved variables, or factors.

H. Davidz. *Enabling Systems Thinking to Accelerate the Development of Senior Systems Engineers.* PhD thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts, 2006.
A. Edmondson. Psychological Safety and Learning Behavior in Work Teams. *Administrative Science Quarterly*, 44(2):350{383, 1999.

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Backup—Sources

Motivation

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Research Methods

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