Systems and Software Design Principles for Large-Scale Mission-Critical Embedded Products from Aerospace and Financial Problem Domains

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Rick Selby
Head of Software Products
Northrop Grumman Space Technology
310-813-5570, Rick.Selby@NGC.com

Adjunct Professor of Computer Science
University of Southern California

Research Investigates Systems and Software Synthesis, Analysis, and Modeling Principles

Overview

- **Systems and software engineering strategies, principles, benefits, and tradeoffs**
- **Example large-scale mission-critical embedded software system**
- **Investigations of synthesis, analysis, and modeling principles**
  - Synthesis: Lifecycle models
  - Synthesis: System architectures
  - Analysis: Reuse analysis
  - Analysis: Structure analysis
  - Modeling: Defect detection techniques
  - Modeling: Measurement and prediction
- **Conclusions and future work**

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Research Investigates Systems and Software Engineering Principles, Benefits, and Tradeoffs

	PRINCIPLES		BENEFITS and TRADEOFFS
SYNTHESIS	<u>Lifecycle models</u>: Frequent synchronized design cycles and system releases	Enables?	Organization of and parallelization within large-scale projects; Rapid feedback and innovation; Visibility into stabilization and handoffs
SYNTHESIS	<u>System architectures</u>: Layered system architectures containing embedded meta-language programs and interpreters	Enables?	User-customizability; Multi-platform portability; Automated testing
ANALYSIS	<u>Reuse analysis</u>: Reconfigurable component-driven development	Enables?	Sustainable multi-project reuse; Lower component defect rates; Lower component development effort
ANALYSIS	<u>Structure analysis</u>: Inter-component connectivity analysis	Enables?	Lower component defect rates; Lower component defect correction effort; Lower component development effort
MODELING	<u>Defect detection techniques</u>: Disciplined team-based peer reviews	Enables?	Early lifecycle defect detection; Low out-of-phase defect rates; High return-on-investment for prevention
MODELING	<u>Measurement and prediction</u>: Automated measurement-driven analysis infrastructure using predictive models	Enables?	Early identification of high defect or high effort components; Statistical process control; Pro-active process guidance

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Organizational Charter Focuses on Embedded Software Products

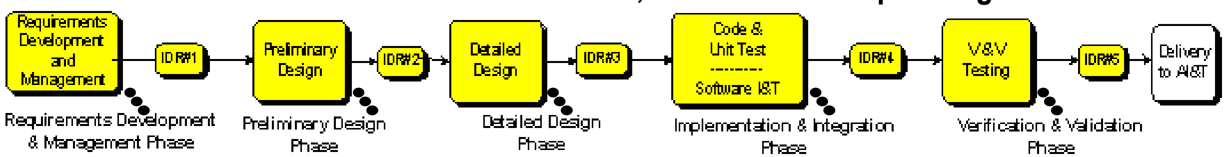
- Embedded software for
  - Advanced robotic spacecraft platforms
  - High-bandwidth satellite payloads
  - High-power laser systems
- Emphasis on both system management and payload software
- Reusable, reconfigurable software architectures and components
- Languages: O-O to C to asm
- CMMI Level 5 for Software in February 2004; ISO/AS9100; Six Sigma
- High-reliability, long-life, real-time embedded software systems

Software Development Lab

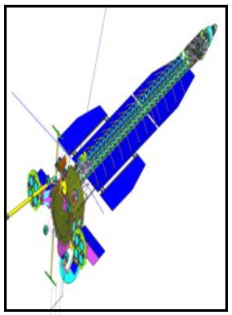
Software Analysis

Software Peer Review

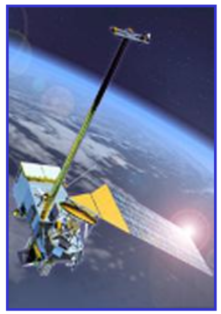
Software Process Flow for Each Build, with 3-15 Builds per Program



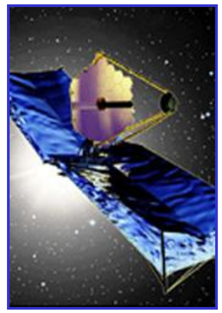
Prometheus / JIMO



NPOESS



JWST



EOS Aqua/Aura

Chandra

GeoLITE

AEHF

MTHEL

Airborne Laser

Restricted

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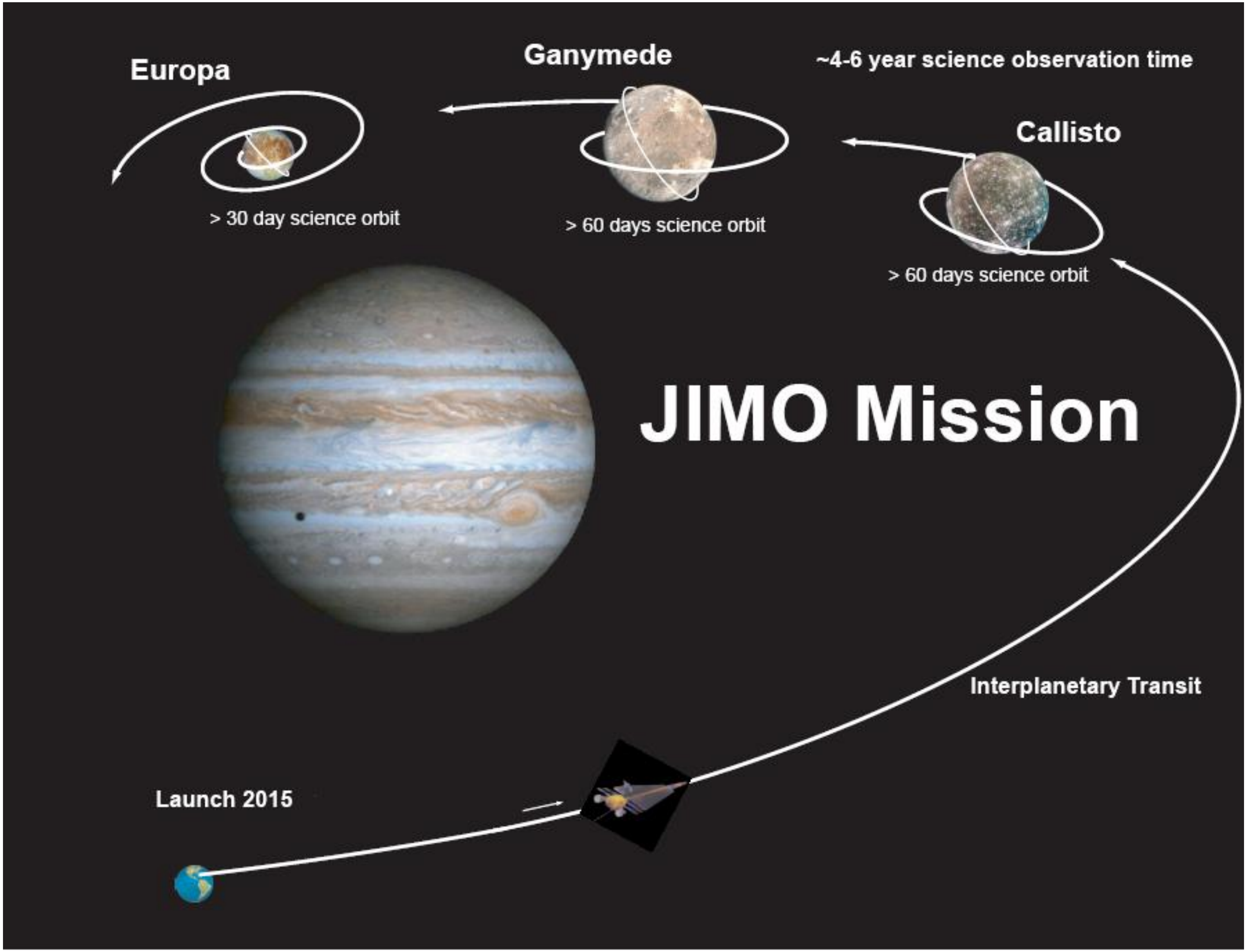
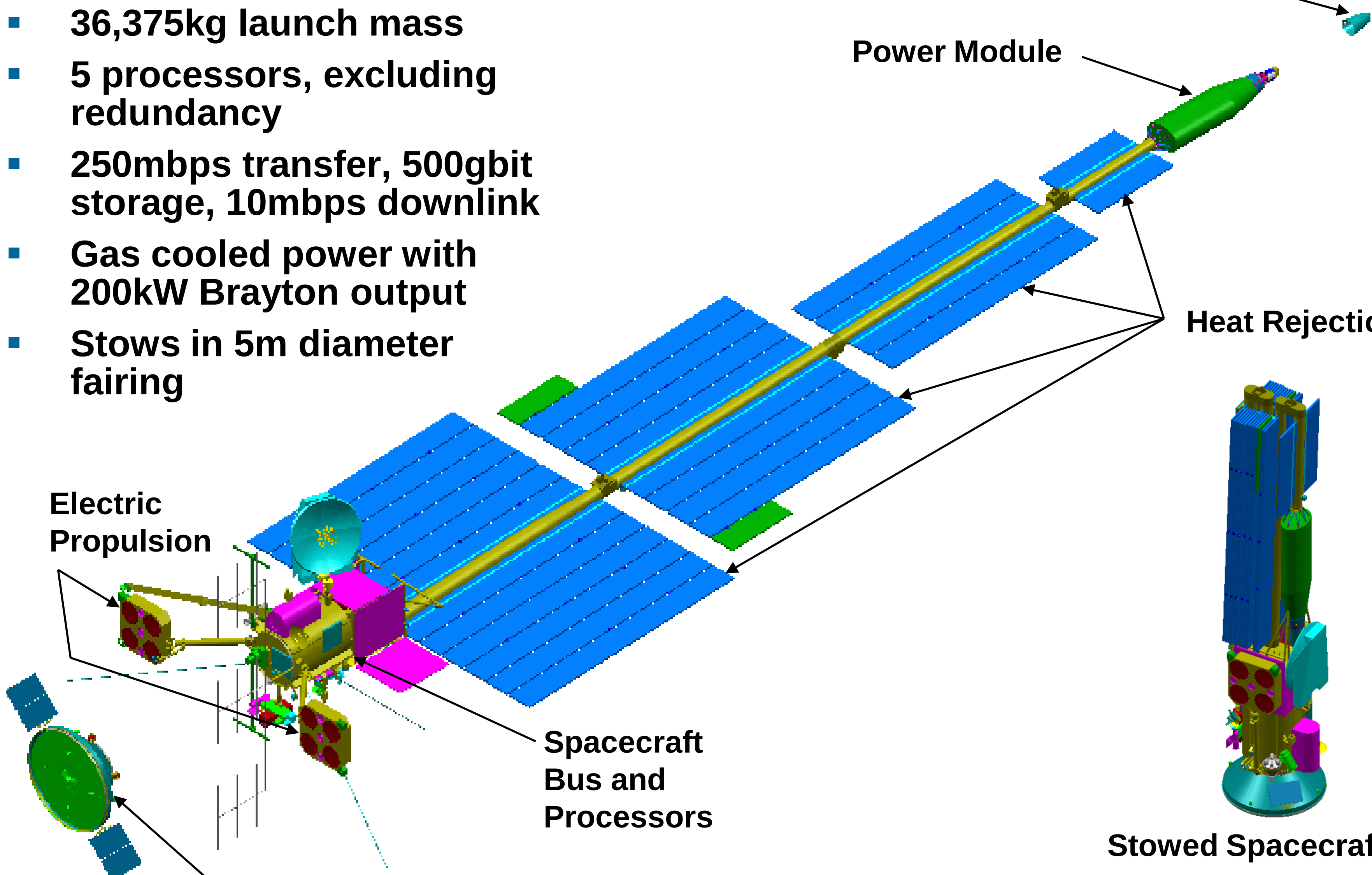
Prometheus Spacecraft Supports Jupiter JIMO Mission over 9 to 14 Year Duration



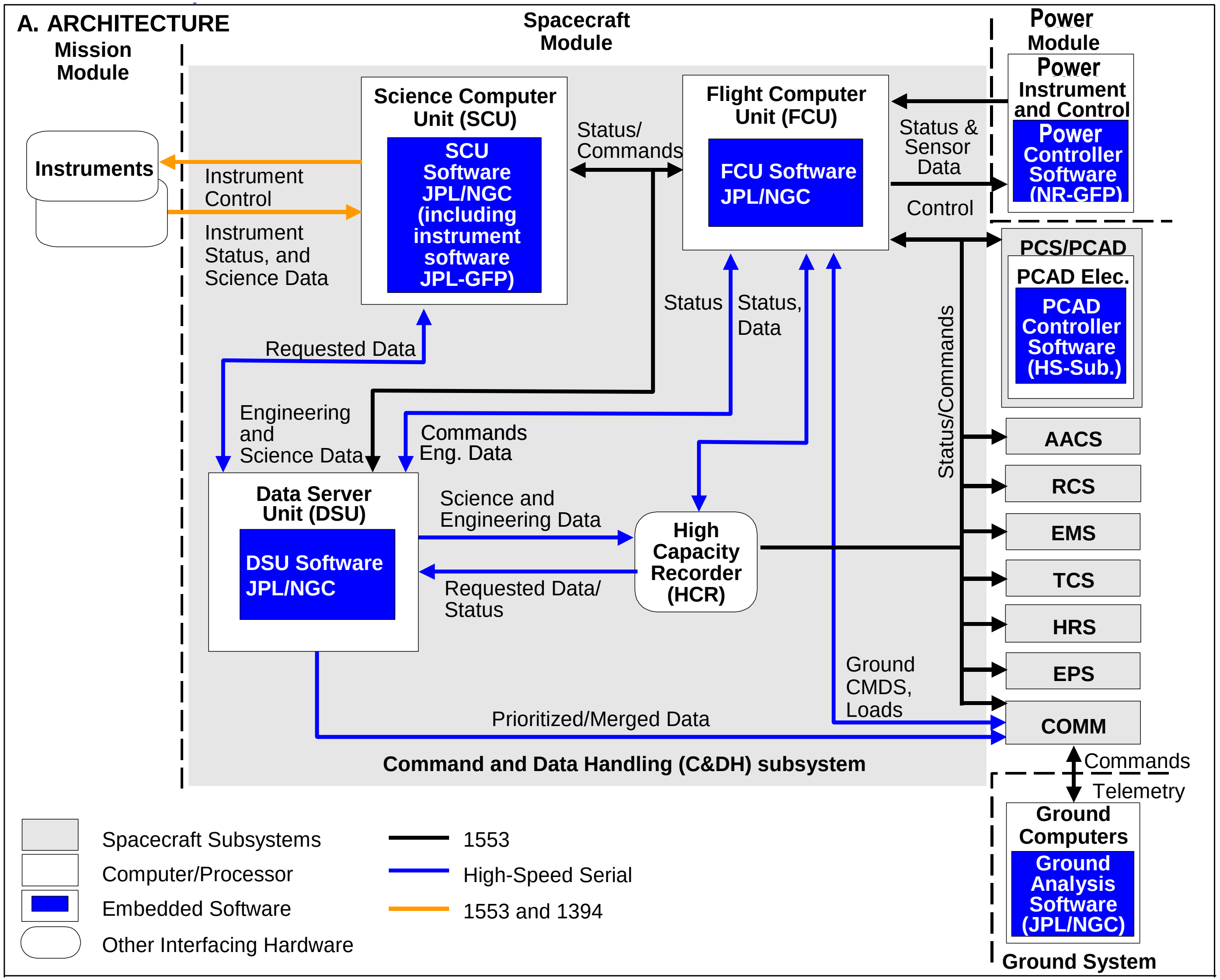
Prometheus Spacecraft for JIMO and Related Missions Enables Data-Intensive Science

- Spacecraft configuration PB1
  - 58m length
  - 36,375kg launch mass
  - 5 processors, excluding redundancy
  - 250mbps transfer, 500gbit storage, 10mbps downlink
  - Gas cooled power with 200kW Brayton output
  - Stows in 5m diameter fairing



Architecture Defines 5 Processors: Flight, Science, Data, Power Generation, and Power Distribution

- **Embedded software implements functions for commands & telemetry, subsystem algorithms, instrument support, data management, and fault protection**
- **Size of on-board software growing to accelerate data processing and increase science yield**
- **Software "adds value" to mission by enabling post-delivery changes to expand capabilities and overcome hardware failures**



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- Lifecycle models: Frequent synchronized design cycles and system releases

Enables?

- Organization of and parallelization within large-scale projects
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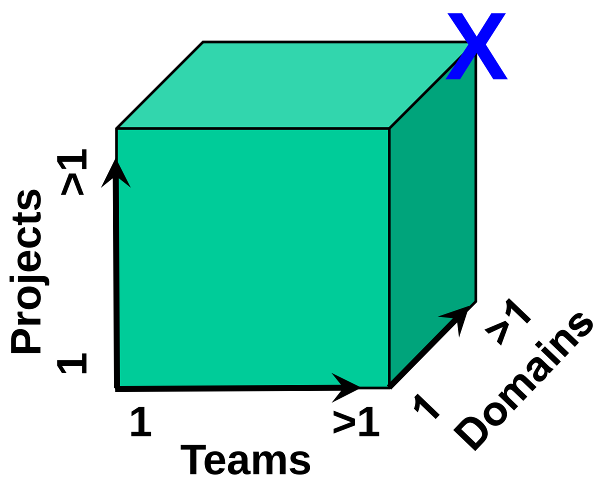
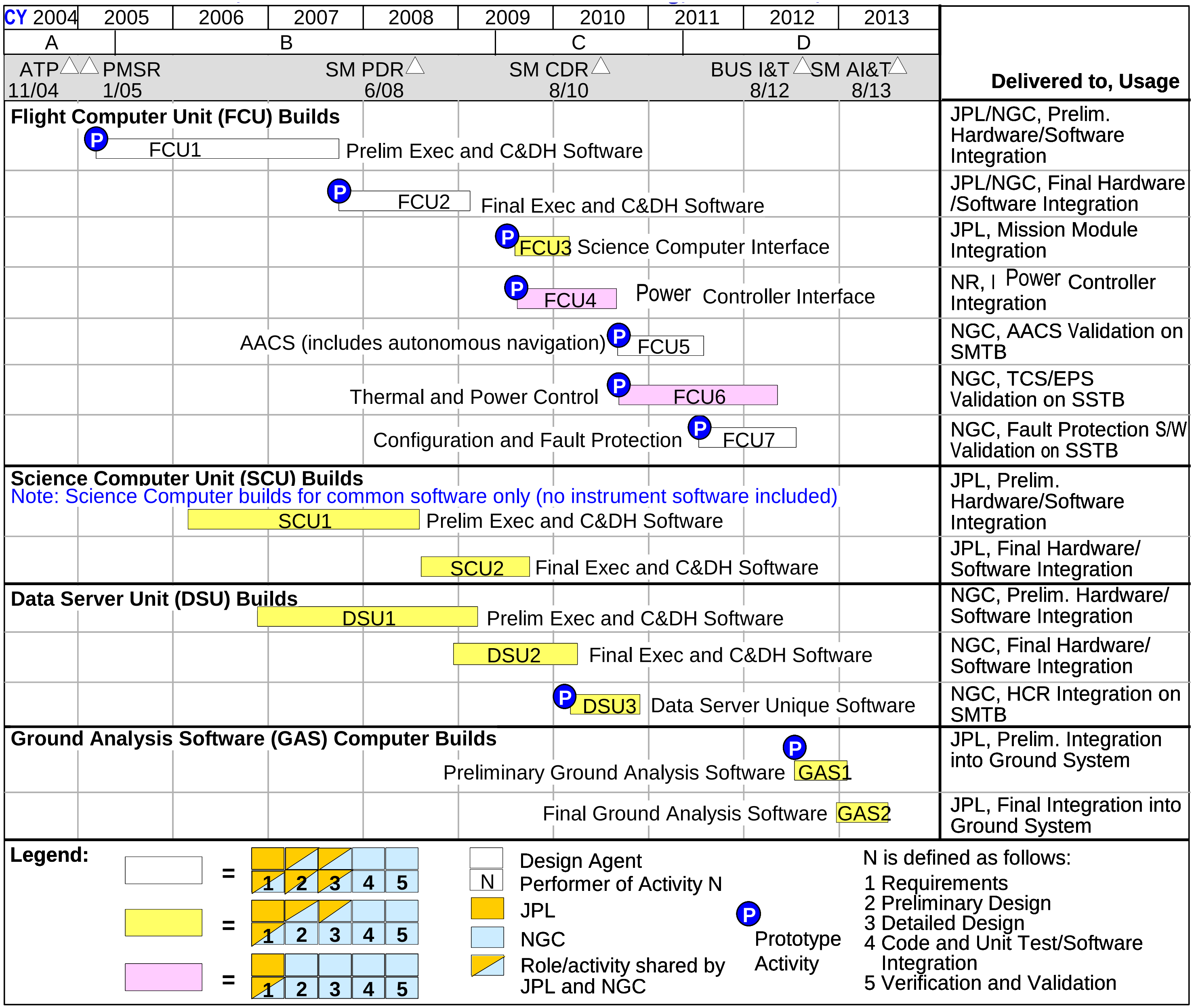


Incremental Software Builds Deliver Early Capabilities and Accelerate Integration and Test



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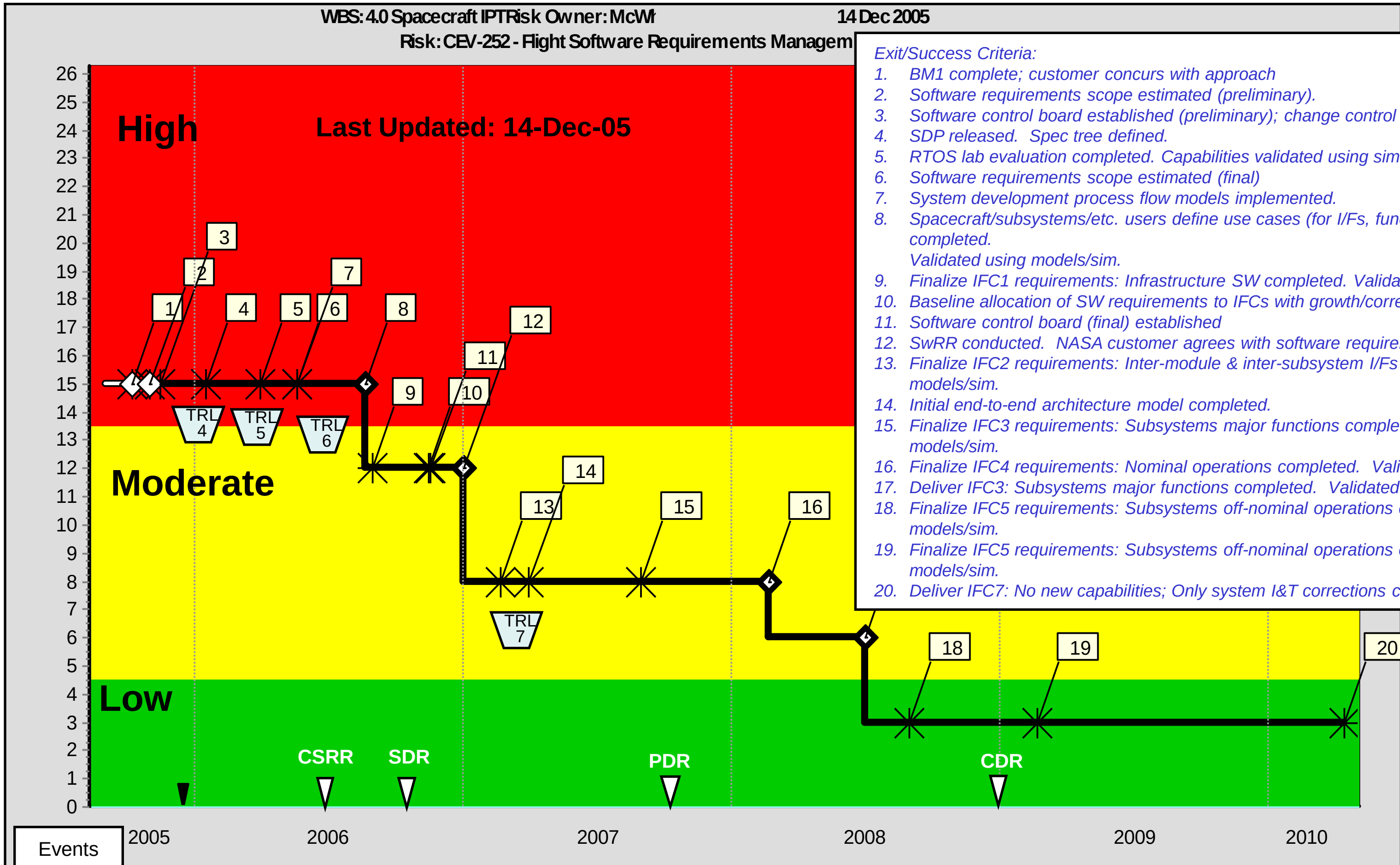
Projects Define Risk Mitigation "Burn Down" Charts with Specific Tasks and Exit Criteria



Exit/Success Criteria:

1. *BM1 complete; customer concurs with approach*
2. *Software requirements scope estimated (preliminary).*
3. *Software control board established (preliminary); change control process established.*
4. *SDP released. Spec tree defined.*
5. *RTOS lab evaluation completed. Capabilities validated using sim.*
6. *Software requirements scope estimated (final)*
7. *System development process flow models implemented.*
8. *Spacecraft/subsystems/etc. users define use cases (for I/Fs, functions, nominal ops, off-nominal ops, etc.) completed.*
   Validated using models/sim.
9. *Finalize IFC1 requirements: Infrastructure SW completed. Validated requirements using models/sim.*
10. *Baseline allocation of SW requirements to IFCs with growth/correction/deficiency completed.*
11. *Software control board (final) established*
12. *SwRR conducted. NASA customer agrees with software requirements.*
13. *Finalize IFC2 requirements: Inter-module & inter-subsystem I/Fs completed. Validated requirements using models/sim.*
14. *Initial end-to-end architecture model completed.*
15. *Finalize IFC3 requirements: Subsystems major functions completed. Validated requirements using models/sim.*
16. *Finalize IFC4 requirements: Nominal operations completed. Validated requirements using models/sim.*
17. *Deliver IFC3: Subsystems major functions completed. Validated capabilities using sim.*
18. *Finalize IFC5 requirements: Subsystems off-nominal operations completed. Validated requirements using models/sim.*
19. *Finalize IFC5 requirements: Subsystems off-nominal operations completed. Validated requirements using models/sim.*
20. *Deliver IFC7: No new capabilities; Only system I&T corrections completed. SW complete for 1st mission.*

Events

1 : Conduct BM1	2 : Estimate software requirements scope (preliminary)
3 : Establish software control board (preliminary)	4 : Release SDP (with spec tree, change process)
5 : Complete RTOS lab evaluation; Validate capabilities using sim	6 : Estimate software requirements scope (final)
7 : Implement system development process flow models	8 : Spacecraft/etc users define/val/sim use-cases (I/F, funct, off-nom, ...)
9 : Finalize/val/sim IFC1 requirements: Infrastructure SW	10 : Baseline allocation of SW requirements to IFCs with growth/correction
11 : Establish software control board (final)	12 : Conduct SwRR
13 : Finalize/val/sim IFC2 requirements: Inter-module & inter-subsystem I/F	14 : Initial end-to-end architecture model
15 : Finalize/val/sim IFC3 requirements: Subsystems major functions	16 : Finalize/val/sim IFC4 requirements: Nominal operations
17 : Deliver IFC3: Subsystems major functions	18 : Finalize/val/sim IFC5 requirements: Subsystems off-nominal operations
19 : Finalize/val/sim IFC6 requirements: System off-nominal operations	20 : Deliver IFC7: No new capabilities; Only corrections; 1st mission ready

Planned Risk Level	Planned (Solid=Linked, Hollow=Unlinked)	Control Points
Actual Risk Level	Completed	Completed

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Enables?

BENEFITS and TRADEOFFS

- User-customizability
- Multi-platform portability
- Automated testing

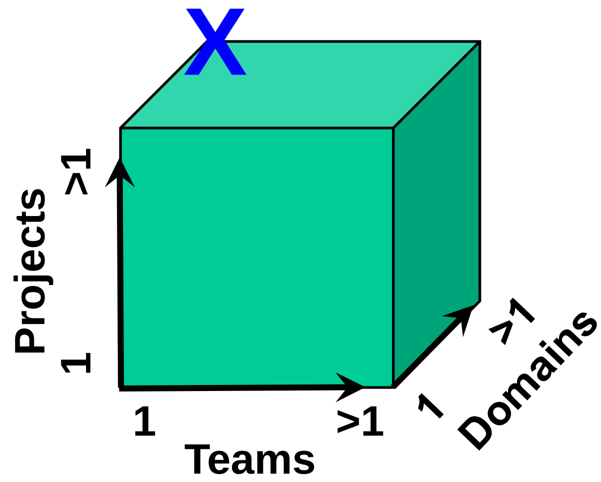
ANALYSIS

- Reuse analysis: Reconfigurable component-driven development
- Structure analysis: Inter-component connectivity analysis

MODELING

- Defect detection techniques: Disciplined team-based peer reviews
- Measurement and prediction: Automated measurement-driven analysis infrastructure using predictive models

SCALING DIMENSIONS



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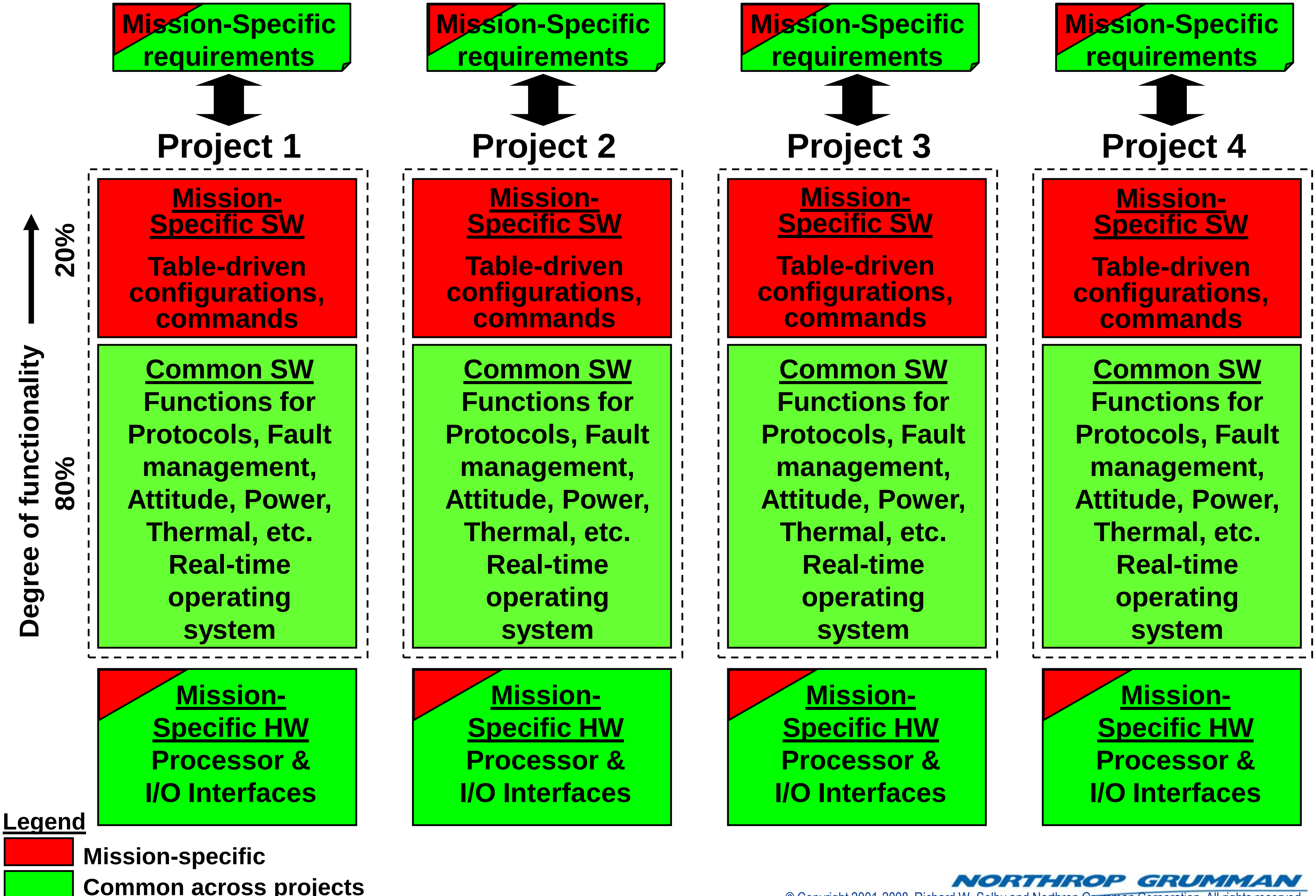
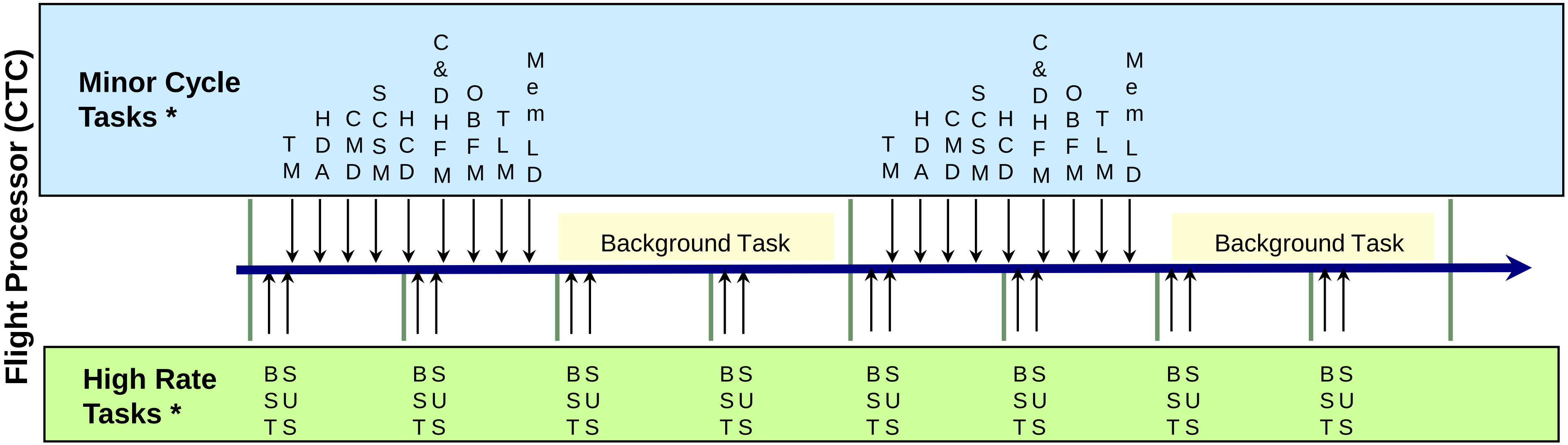
Common Requirements Enable Software Product Lines and Layered Architectures Across Projects



Architecture Uses Simple Task Structure, Deterministic Processing, and Predictable Timeline



- **Three-task structure: 32ms task (high rate), 128ms (minor cycle), and background task**
- **Minor cycle serves as the main workhorse task that executes commands, formats telemetry, and handles fault protection**
- **Minor cycle command processor reads active command sequences and executes individual deterministic commands**
- **>50% margins at system delivery for processor, memory, storage, and bus**

*** Not to scale**

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- **Reuse analysis: Reconfigurable component-driven development**

Enables?

BENEFITS and TRADEOFFS

- **Sustainable multi-project reuse**
- **Lower component defect rates**
- **Lower component development effort**

ANALYSIS (cont.)

- Structure analysis: Inter-component connectivity analysis

MODELING

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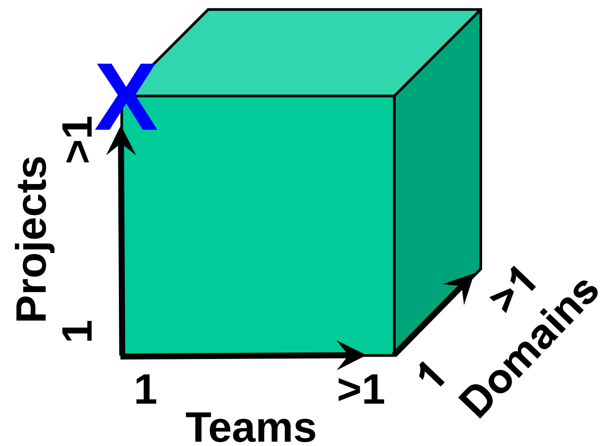

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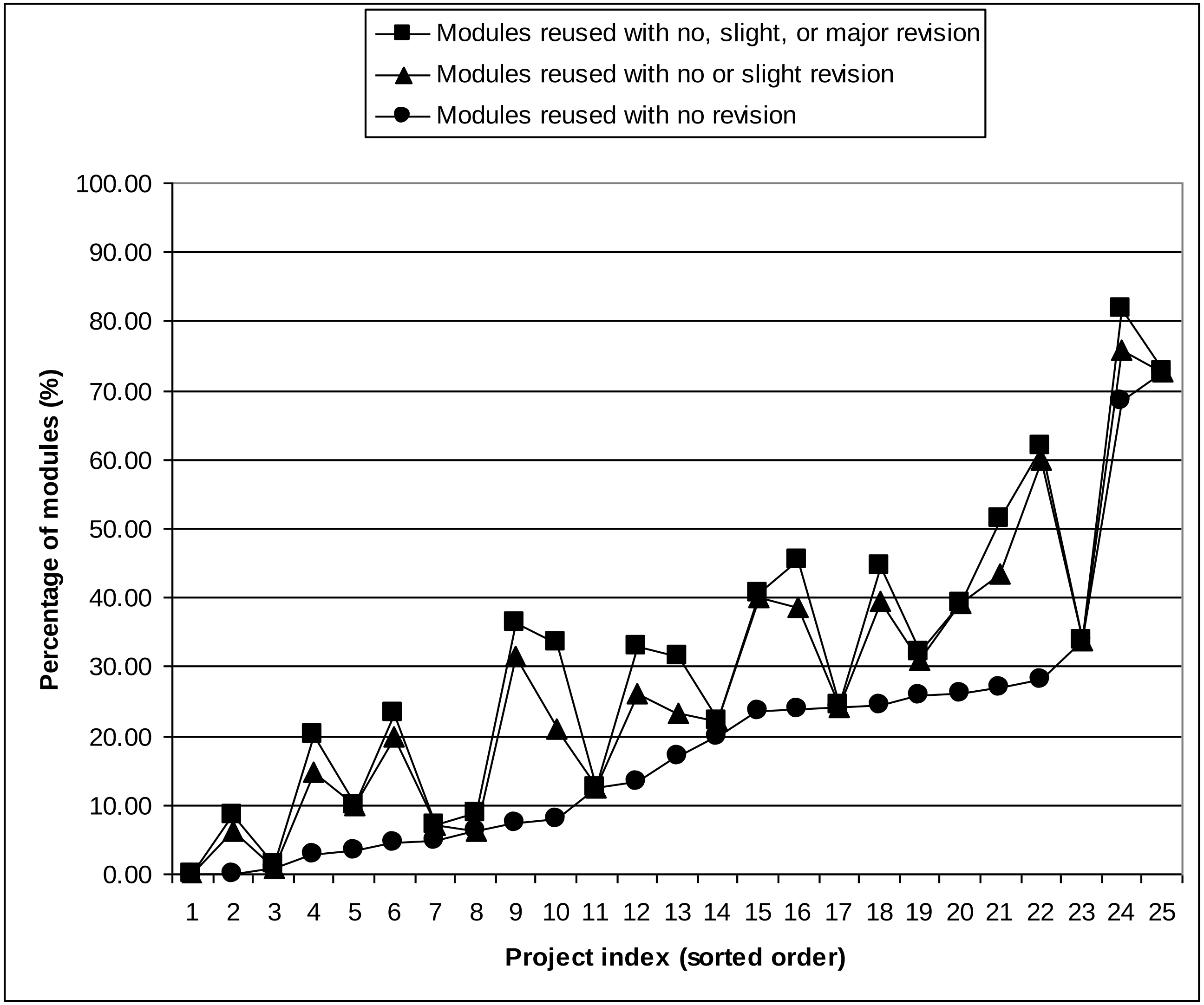
32% of Software Components are Either Reused or Modified from Previous Systems



- **Data from 25 NASA systems**
- **Component origins: 68.0% new development, 4.6% major revision, 10.3% slight revision, and 17.1% complete reuse without revision**

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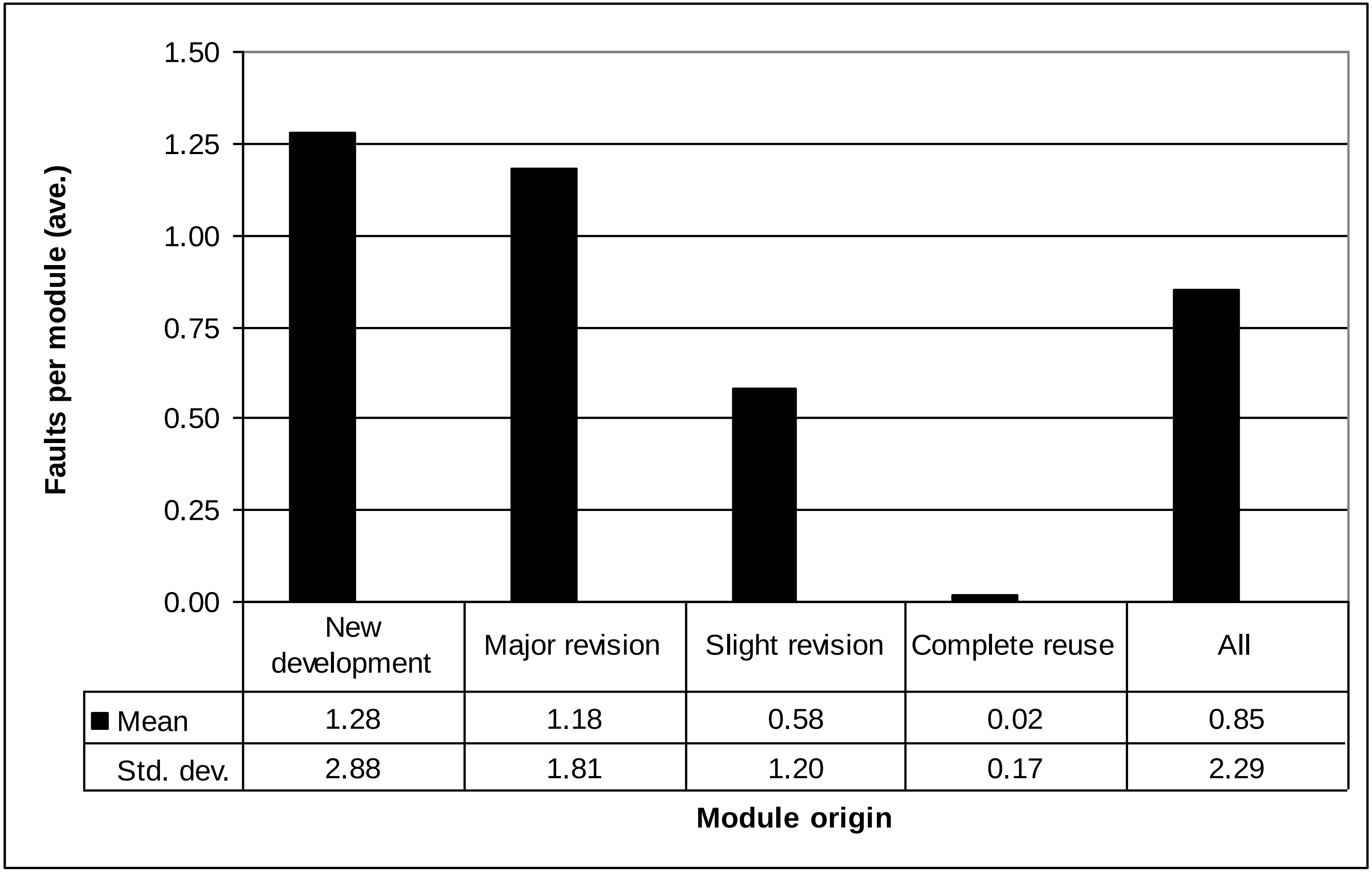
Analyses of Component-Based Software Reuse Shows Favorable Trends for Decreasing Faults



	New development	Major revision	Slight revision	Complete reuse	All
■ Mean	1.28	1.18	0.58	0.02	0.85
Std. dev.	2.88	1.81	1.20	0.17	2.29

- **Data from 25 NASA systems**
- **Overall difference is statistically significant ($\alpha < .0001$). Number of components (or modules) in each category is: 1629, 205, 300, 820, and 2954, respectively.**

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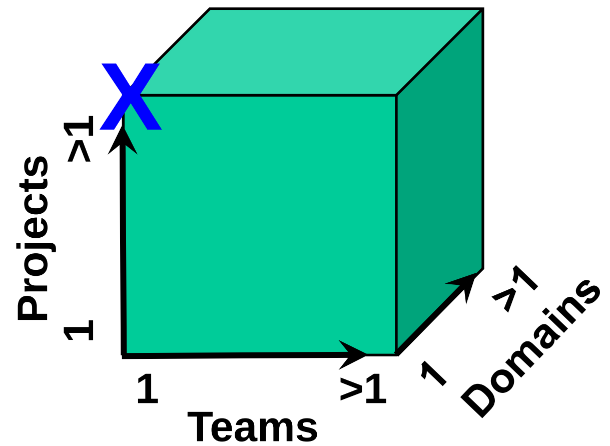
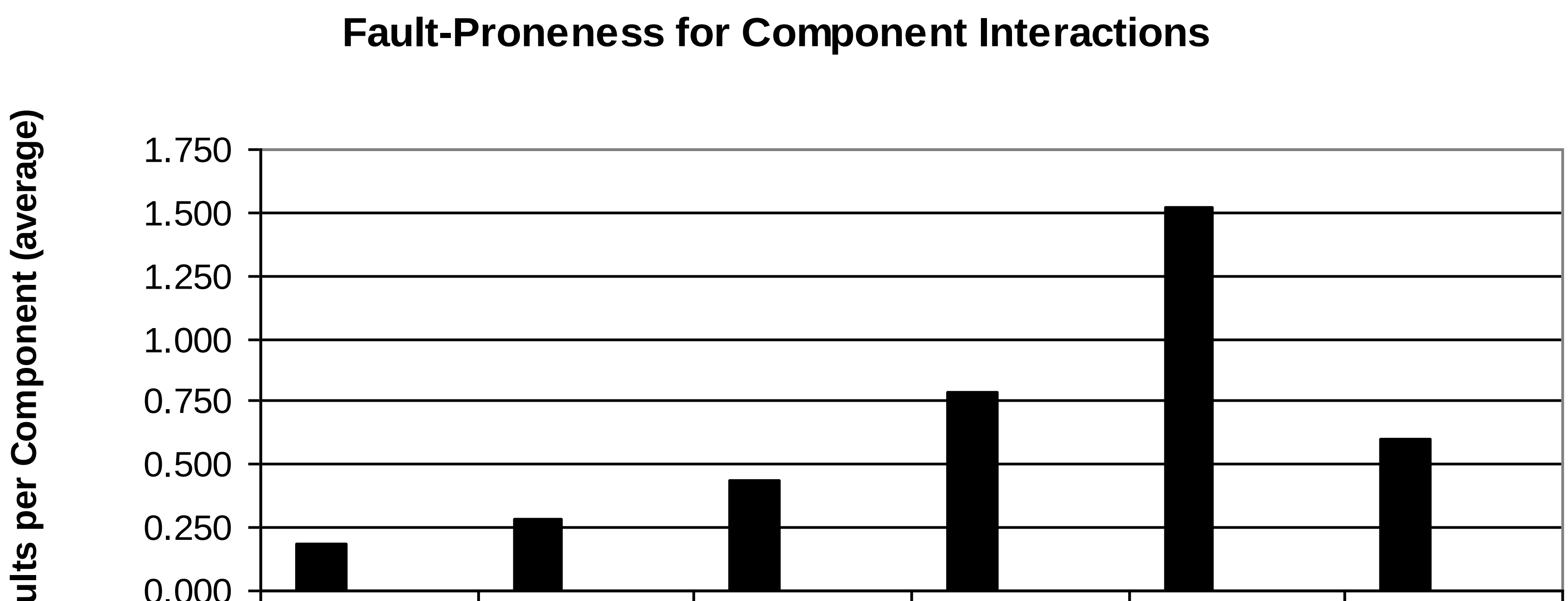


BENEFITS and TRADEOFFS

Structure analysis Enables?

- Lower component defect rates
- Lower component defect correction effort
- Lower component development effort

Analyses of Software Architectures Shows Fault Trends for Component Interactions



	1st Quintile	2nd Quintile	3rd Quintile	4th Quintile	5th Quintile	All
■ Average	0.191	0.280	0.438	0.789	1.524	0.598
Std. Dev.	0.745	0.875	1.358	2.048	3.048	1.809
N	1566	867	1128	920	988	5469

Interactions per Component

- **Data from 23 NASA systems**
- **5469 components analyzed and categorized by quintiles**

Absolute

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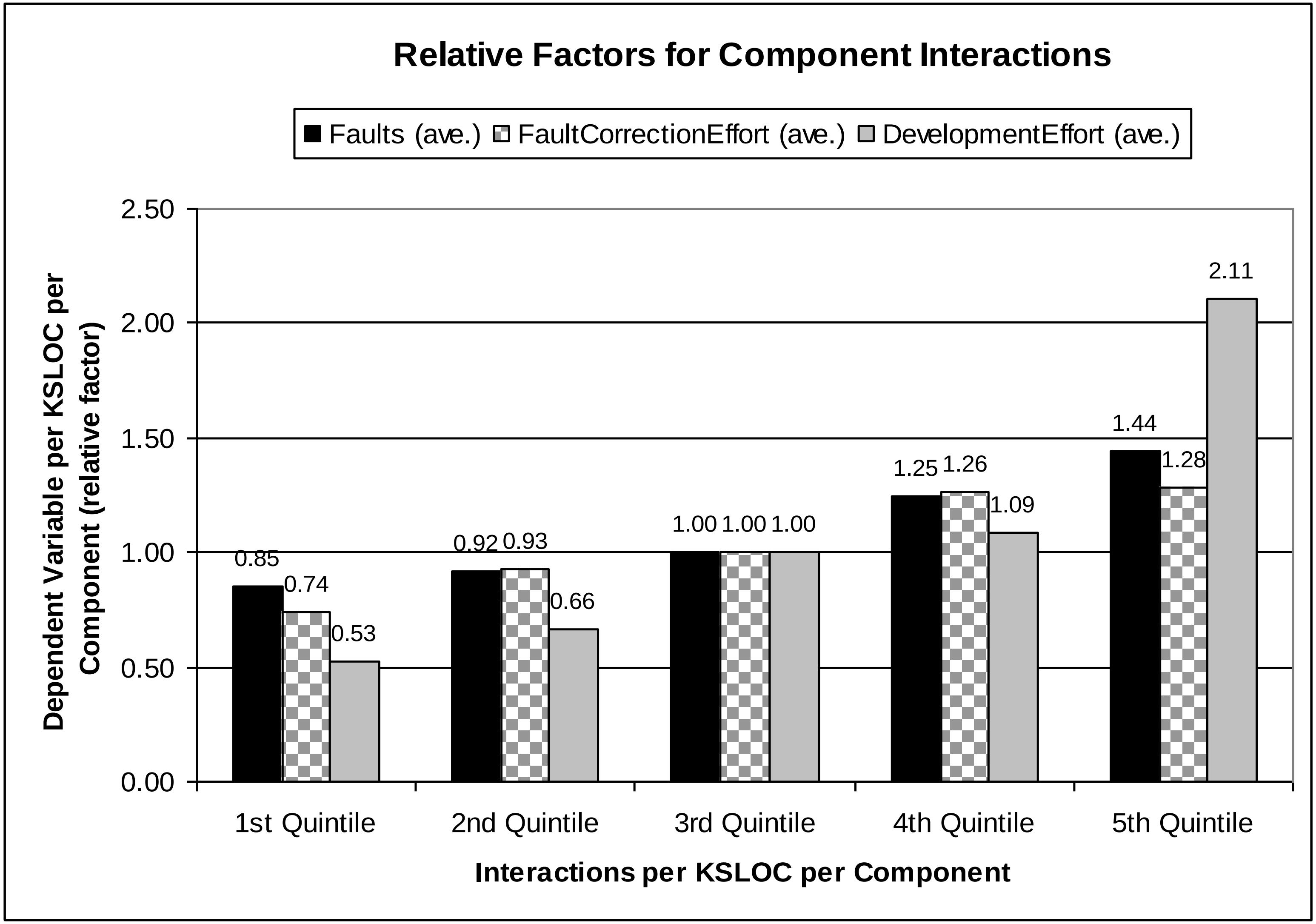
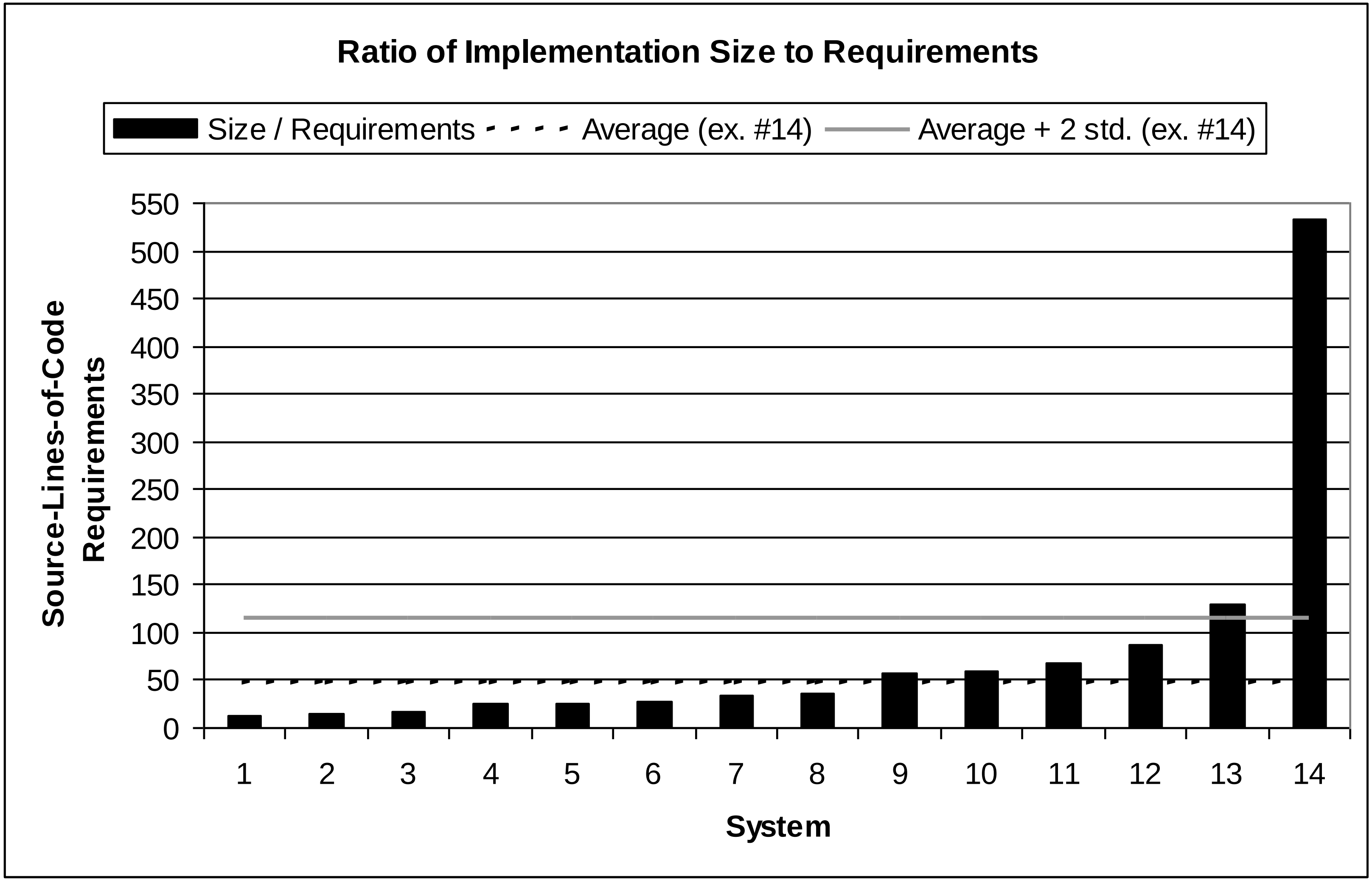
Analyses of Software Architectures Shows Fault Trends for Component Interaction Relative Factors



- **Data from 23 NASA systems**
- **5469 components analyzed and categorized by quintiles**

Absolute norm-norm

Analyses of Software Requirements Shows Leading Indicators for Implementation Scope and Priorities



- Data from 14 NASA systems
- Ratio of implementation size to software requirements has 81:1 average and 35:1 median; Excluding system #14, the ratio has 46:1 average and 33:1 median
- Ratio of software requirements to system requirements has 6:1 average

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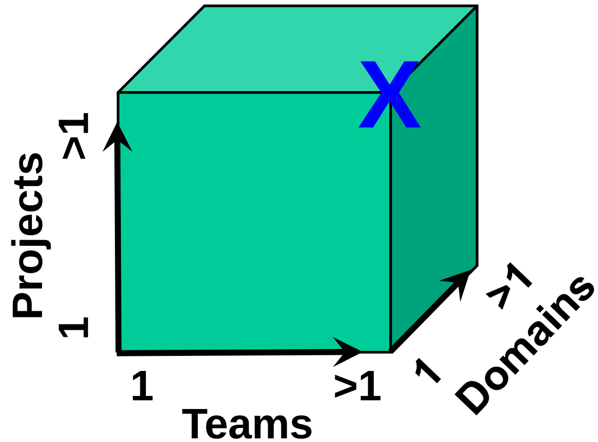
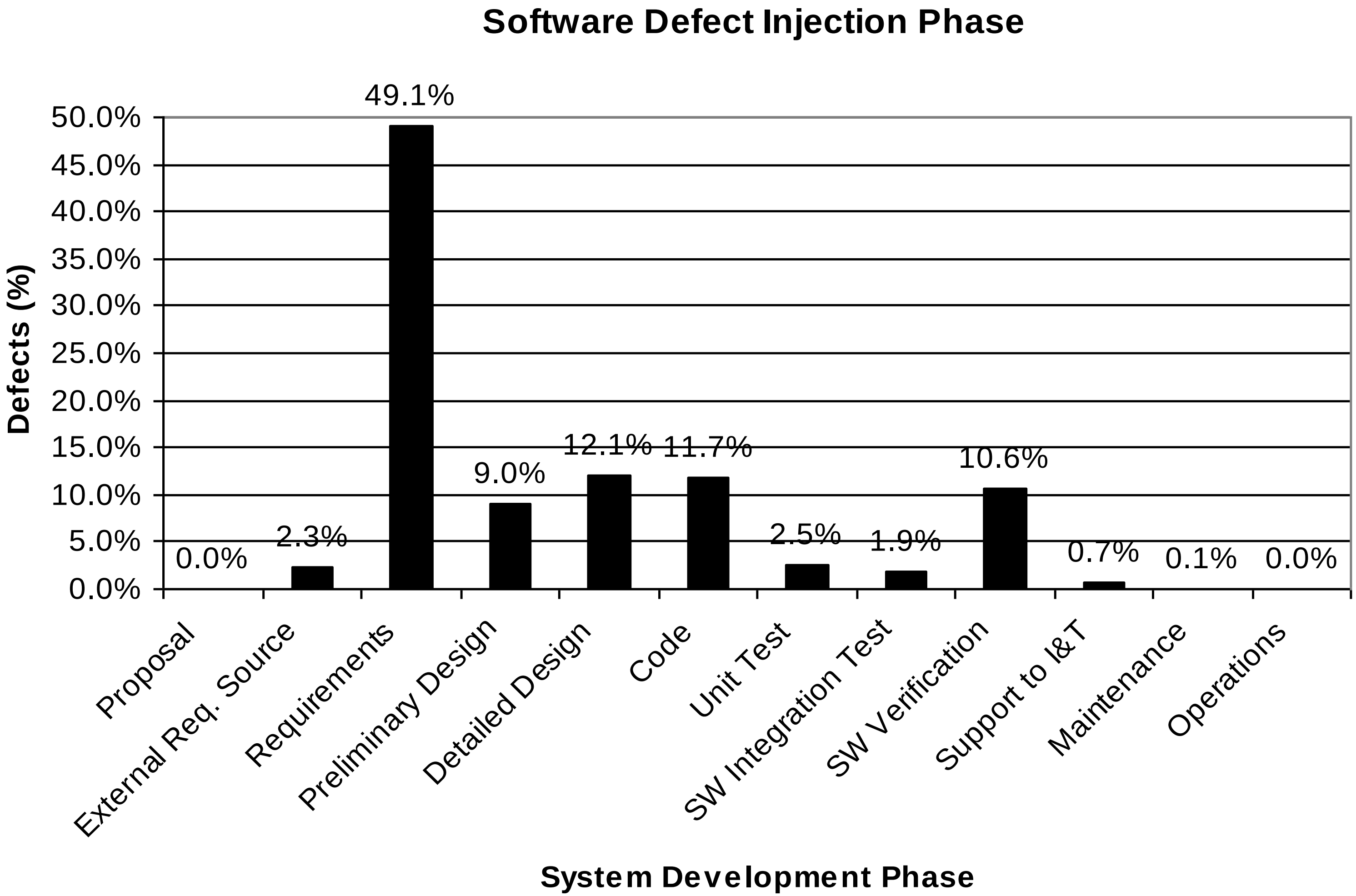


BENEFITS and TRADEOFFS

- Early lifecycle defect detection
- Low out-of-phase defect rates
- High return-on-investment for prevention

Analyses of Software Defect Injection Phases Reveals Distributions



- **Distribution of software defect injection phases based on using peer reviews across 12 system development phases**
- **3418 defects, 731 peer reviews, 14 systems, 2.67 years**
- **49% of defects injected during requirements phase**

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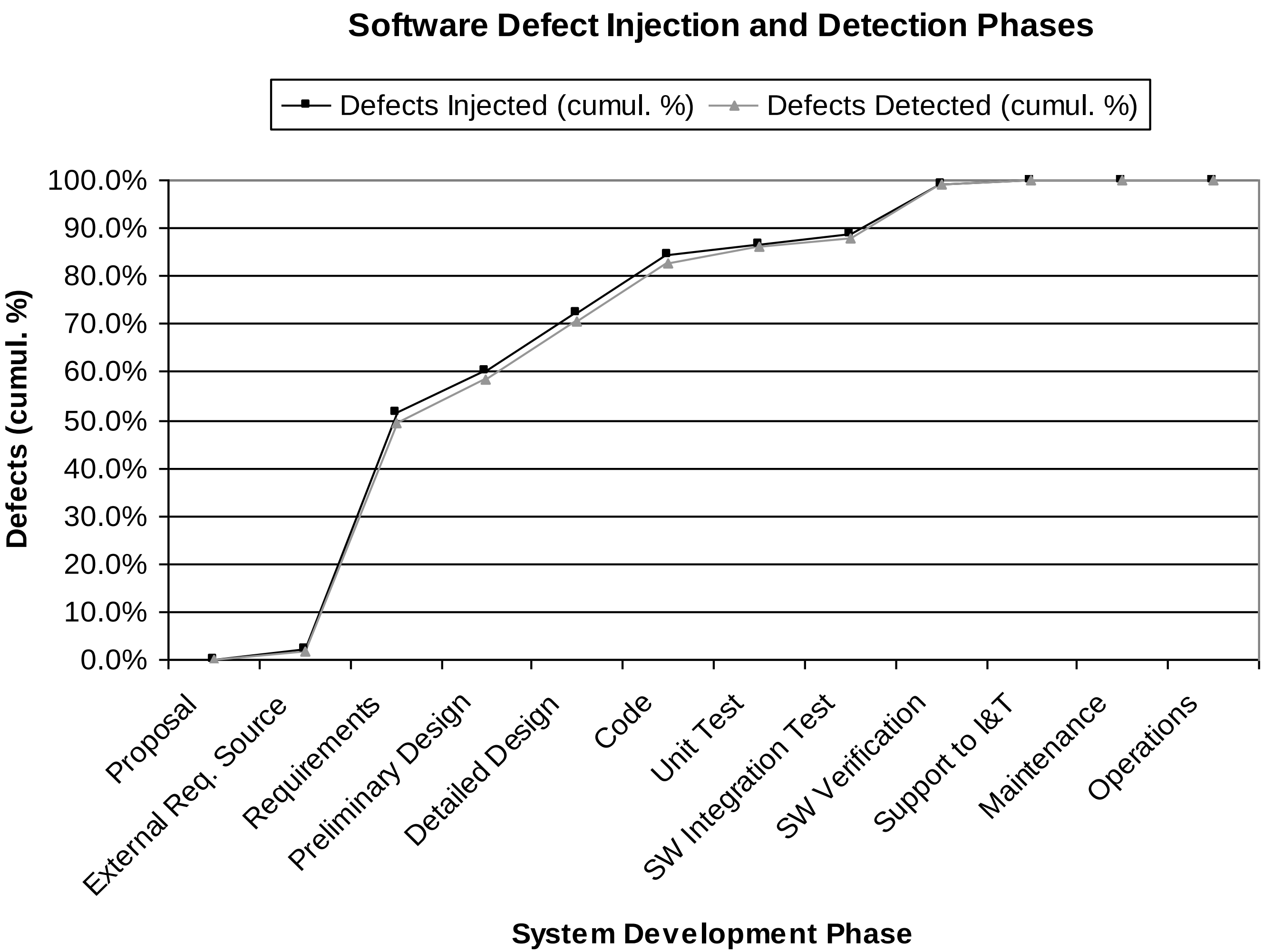
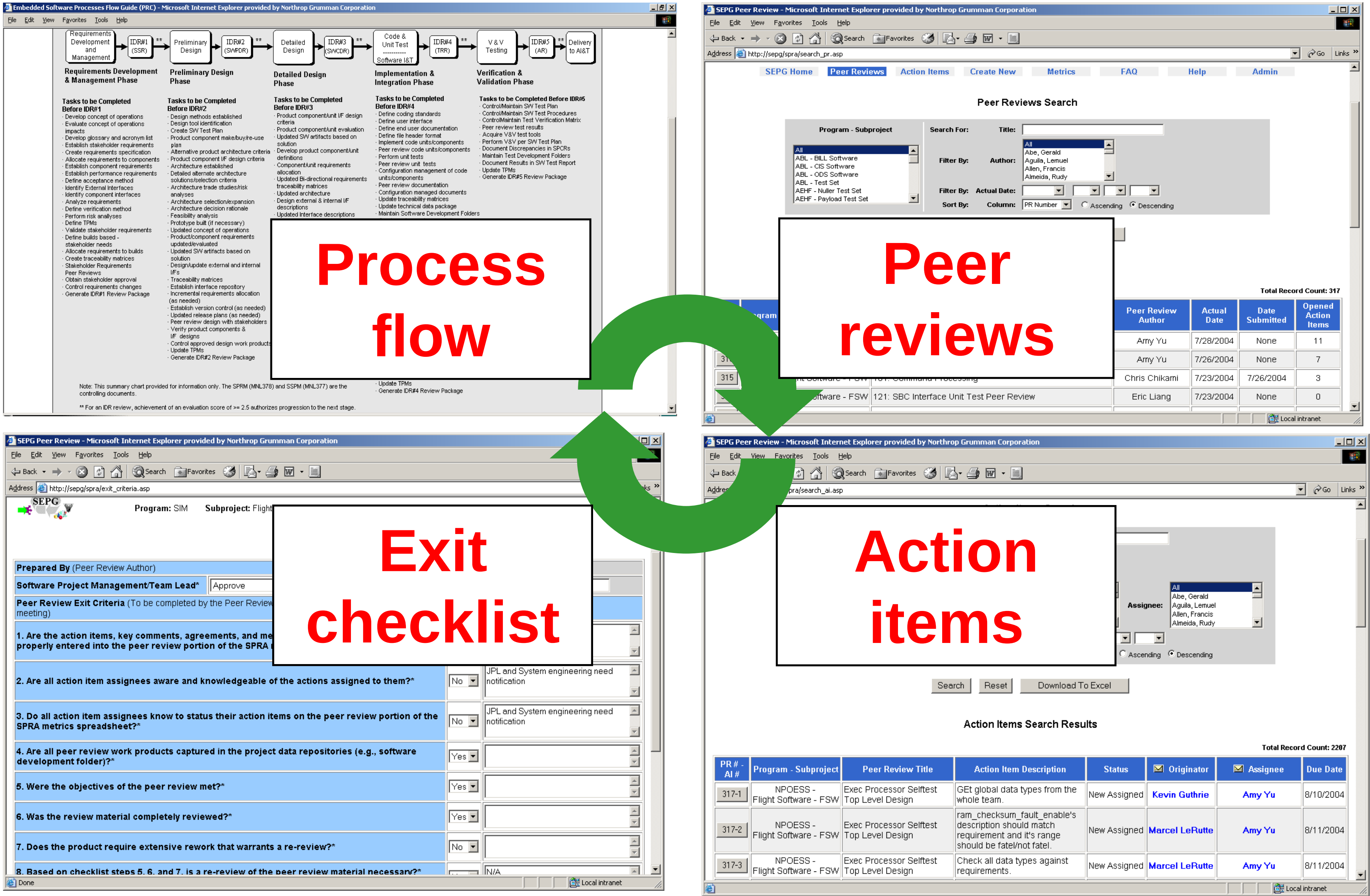
Analyses of Software Defect Injection and Detection Phases Reveal Distributions and Gaps



- Cumulative distribution of software defect injection and detection phases based on using peer reviews across 12 system development phases
- 3418 defects, 731 peer reviews, 14 systems, 2.67 years
- 50% defects injected by requirements, 70% by detailed design; Gap shows leakage

Web-Based Workflow Tools and Infrastructure Support Software Process Flow



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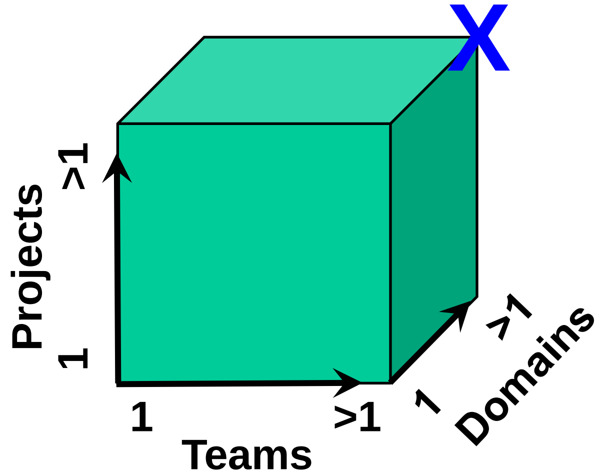

BENEFITS and TRADEOFFS

- Early identification of high defect or high effort components
- Statistical process control
- Pro-active process guidance

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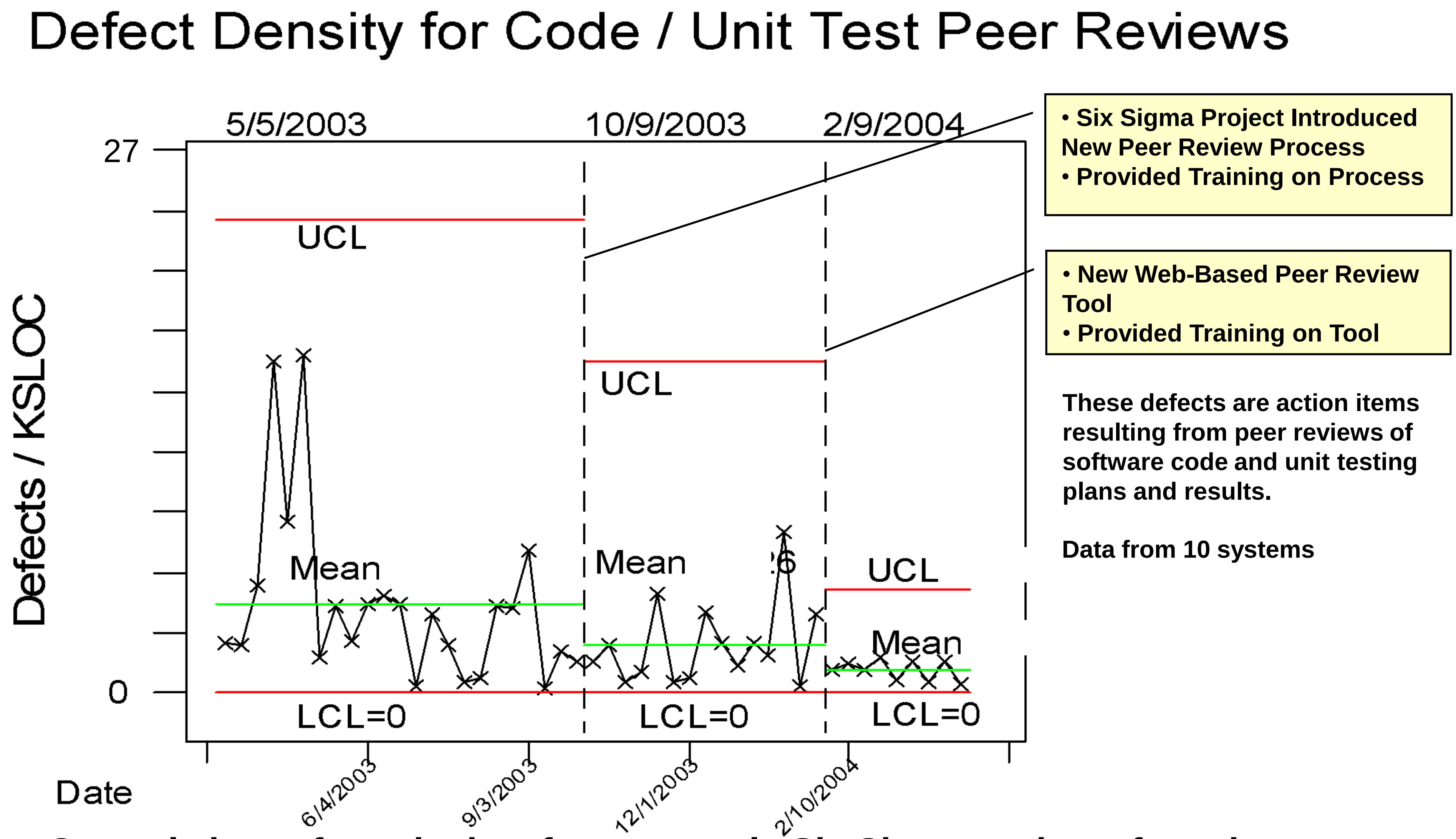
Data-Driven Statistical Analyses Identify Trends, Outliers, and Process Improvements for Defects



- Control chart of metric data from example Six Sigma projects focusing on fault (or defect) density in peer reviews of software components
- Process improvements decreased variances and decreased means

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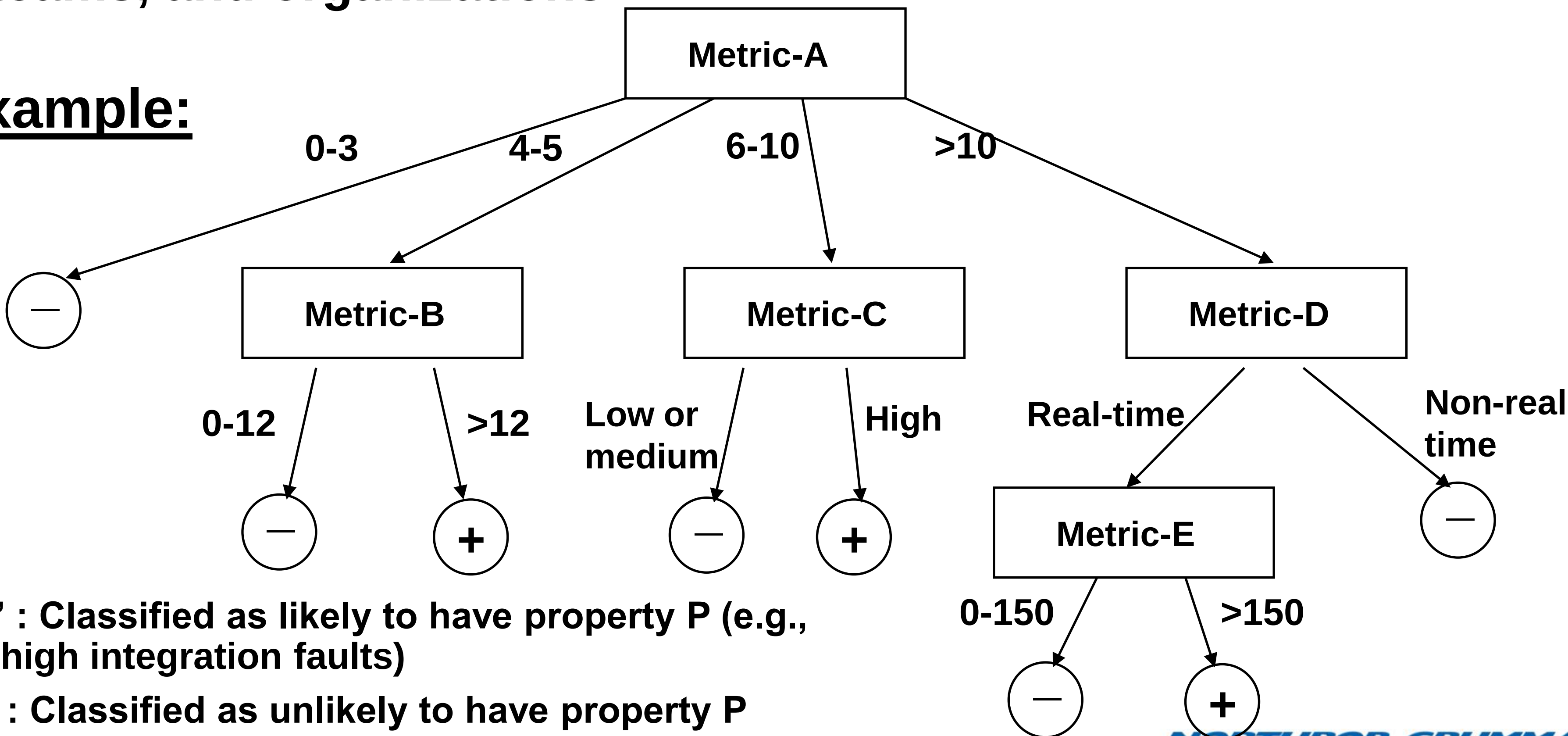
Measurement-Driven Decision Models (Trees, Networks) Predict High-Risk Software Components

- **Focus on high-payoff areas: the 80:20 rule**
- **Generate decision trees or networks automatically**
  - Scalable to large systems
  - Leverage previous experience and calibrate to new environments
- **Integrate measurements from processes, products, projects, teams, and organizations**

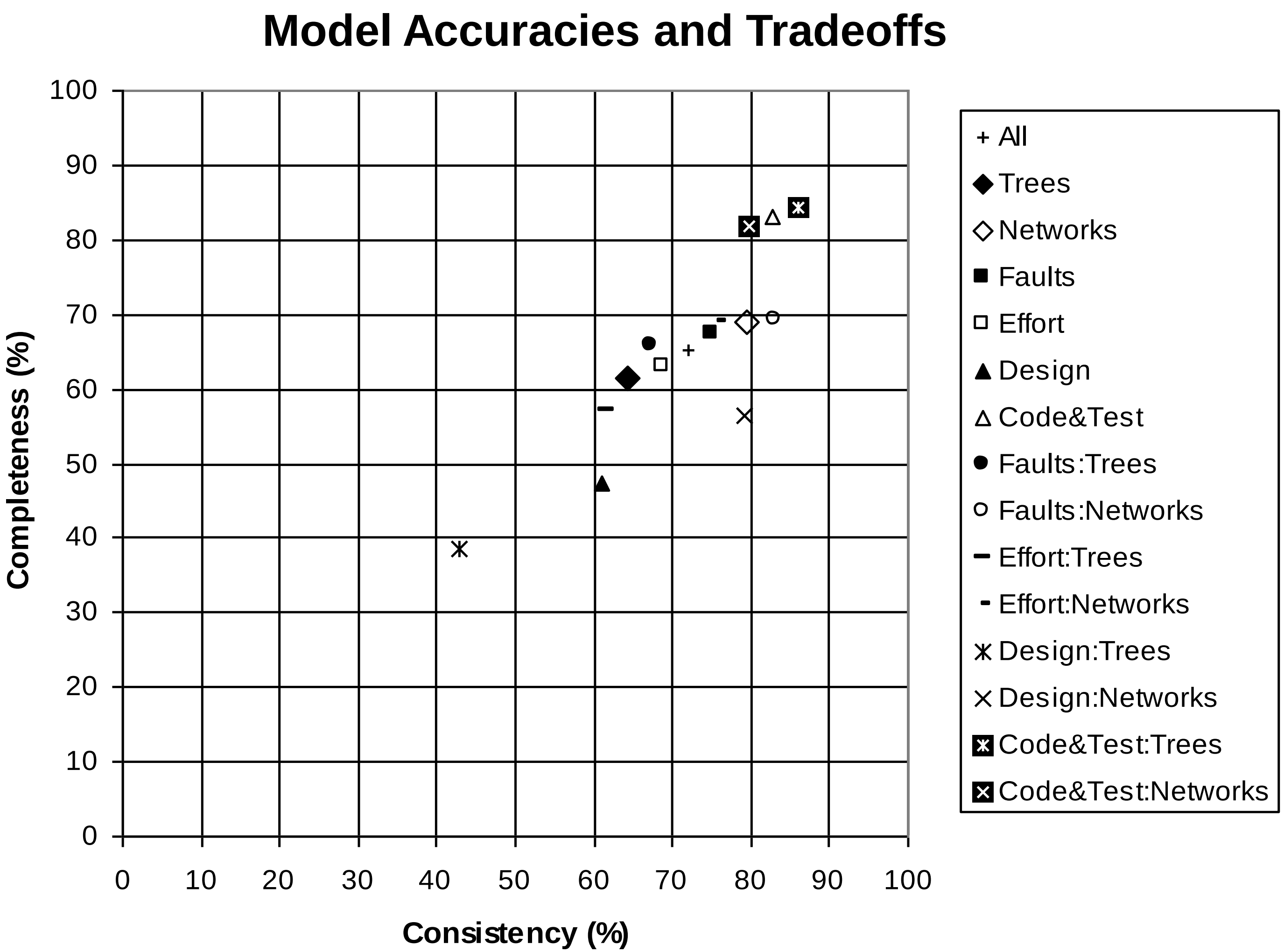
<u>Example:</u>



"+" : Classified as likely to have property P (e.g., high integration faults)

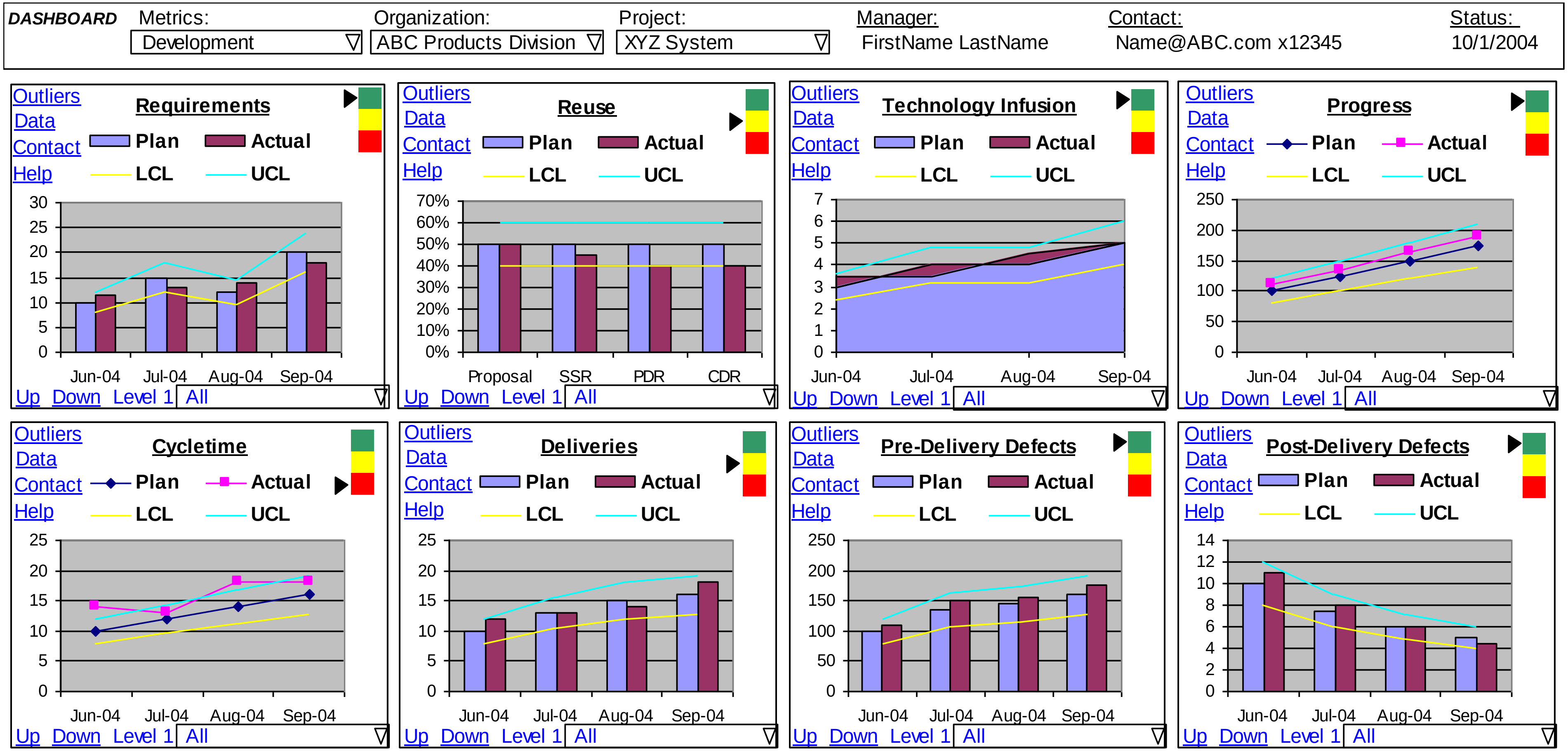
"-" : Classified as unlikely to have property P

Predictive Models Identify Leading Indicators of High-Fault and High-Effort Components



- **Data from 16 NASA systems. 1920 model variations.**
- **Consistency is 100% minus percent false positives. Completeness is 100% minus percent false negatives.**

Interactive Metric Dashboards Provide Framework for Visibility, Flexibility, Integration, Automation



- **Interactive metric dashboards incorporate a variety of information and features to help developers and managers characterize progress, identify outliers, compare alternatives, evaluate risks, and predict outcomes**

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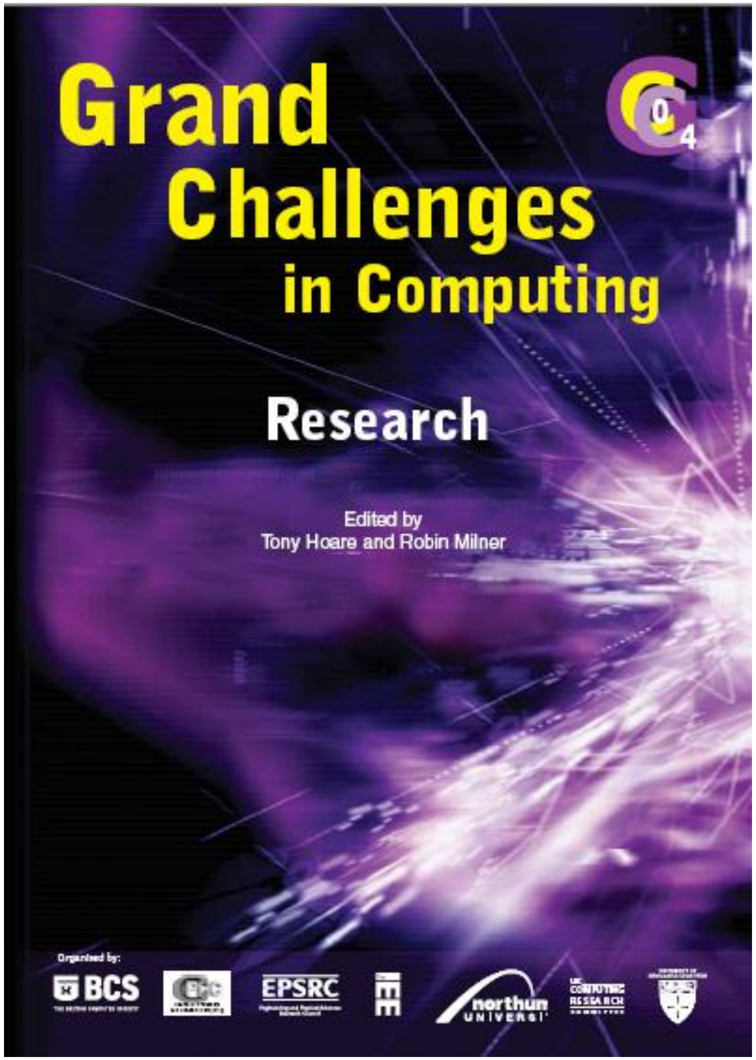
Define "Grand Challenges" Problems for Systems and Software Engineering

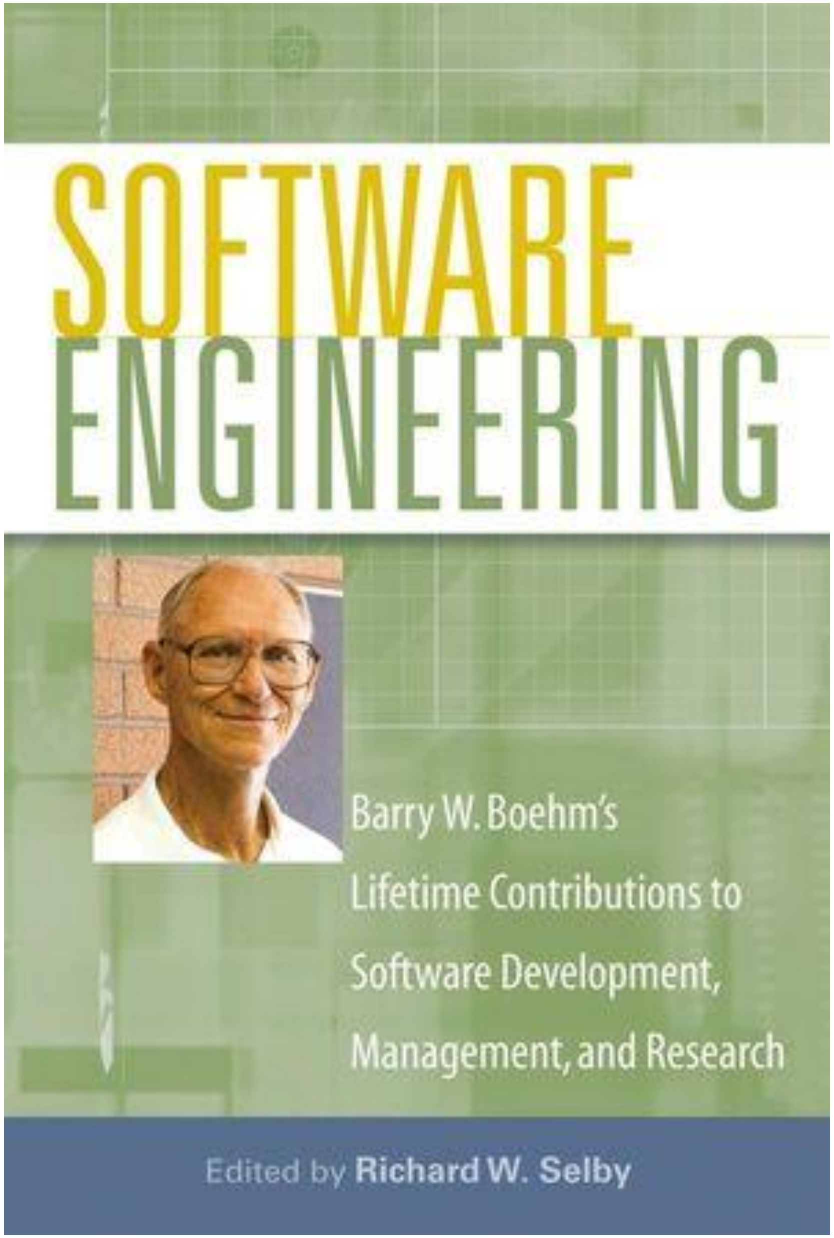
Example from Computing (2004)



Contents

Source: http://www.ukcrc.org.uk/gcresearch.pdf

Software Engineering Book Captures Best Practices for Economics, Quality, Process, Risk Management



- **Richard W. Selby, Editor, <u>Software Engineering: Barry W. Boehm's Lifetime Contributions to Software Development, Management, and Research</u>, IEEE Computer Society and John Wiley & Sons: New York, May 2007, ISBN 9780-4701-48730.**

- **Rick.Selby@NGC.com**