Knowledge Management for Maintenance of Complex Systems

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21 April 2009

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Abstract

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This presentation will review the use of knowledge management in the development and support of Condition Based Maintenance (CBM) systems for complex systems with particular emphasis on the experience of the development of the Fault Model for the Boeing 777 an d 787.

The presentation is divided into three sections:

1. ***Overview of diagnostic problem, accuracy assessment methodology and selected approach***

2. ***Review of experience of building fault models and Central Maintenance Computer for large commercial aircraft***

3. ***Review of the key functions and usage scenarios for a typical CBM Knowledge Management System***

The presentation will conclude with a short discussion of future directions for CBM Knowledge Management Systems.

Overview of Diagnostic Systems

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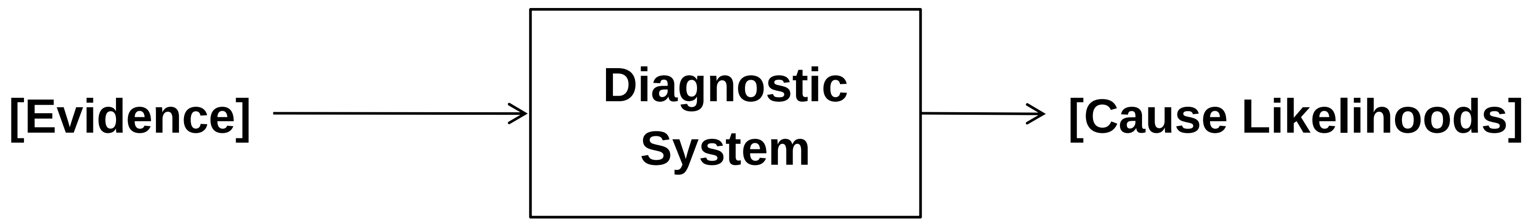
Diagnostic System Overview



The **Evidence** vector is a collection of binary condition indicators (system states, bucketized parameters, abnormality indicators, test results, operator complaints, etc)

Note: Evidence indicators are actually tri-state: Present, Absent, Unknown.

The **Cause Likelihoods** vector is a collection of possible causes with the likelihood for each indicating the relative likelihood that it is the cause of the evidence.

Diagnostic System Overview – Model Based

[Evidence] → **Diagnostic System** → [Cause Likelihoods]

↑ [Fault Model]

The **Fault Model** is a collection of objects and relations that are used by the diagnostic system so that the <u>algorithms are independent of the particular system being diagnosed</u>.

Diagnostic Error Analysis

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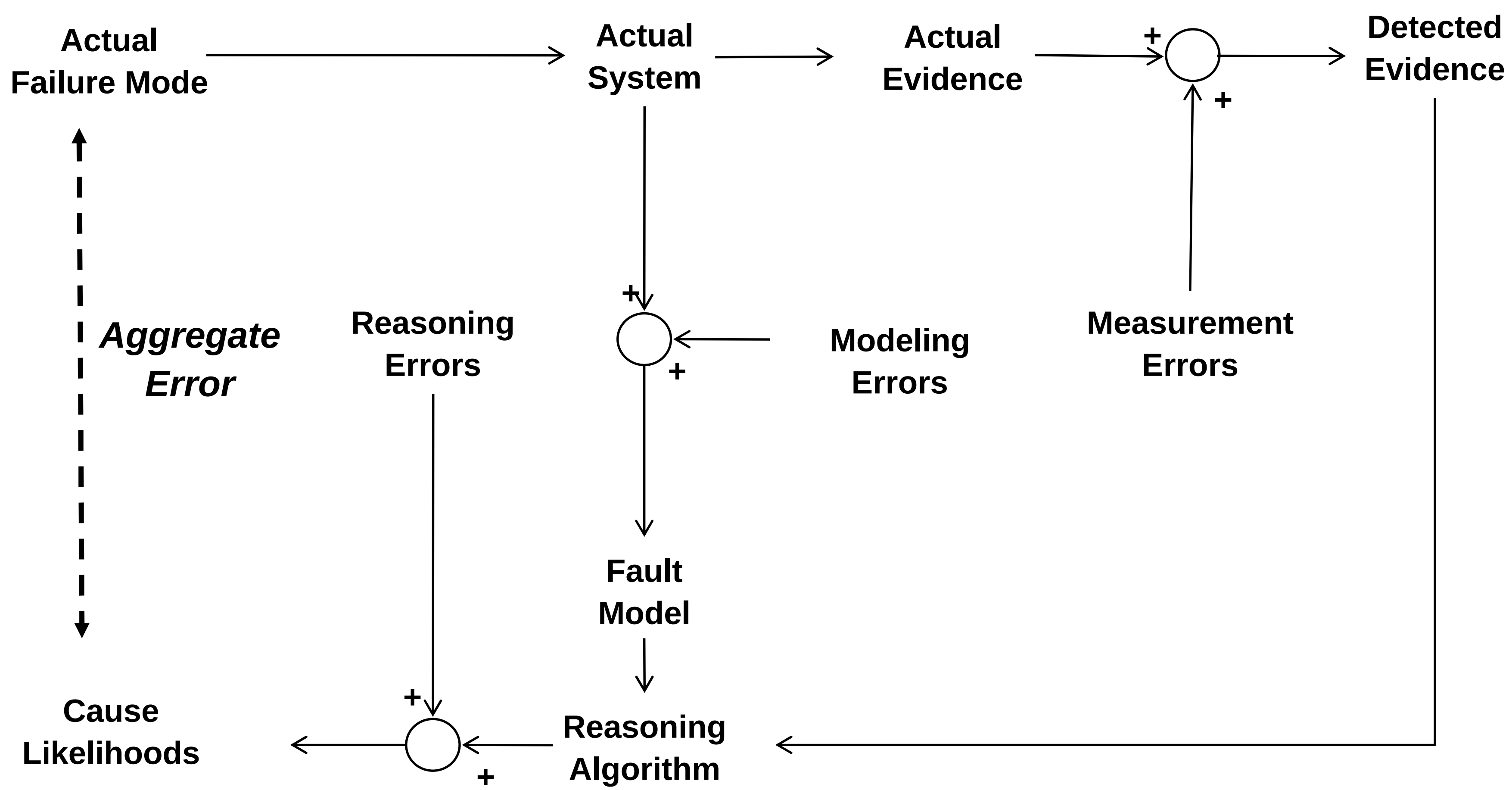

Diagnostic Error Analysis

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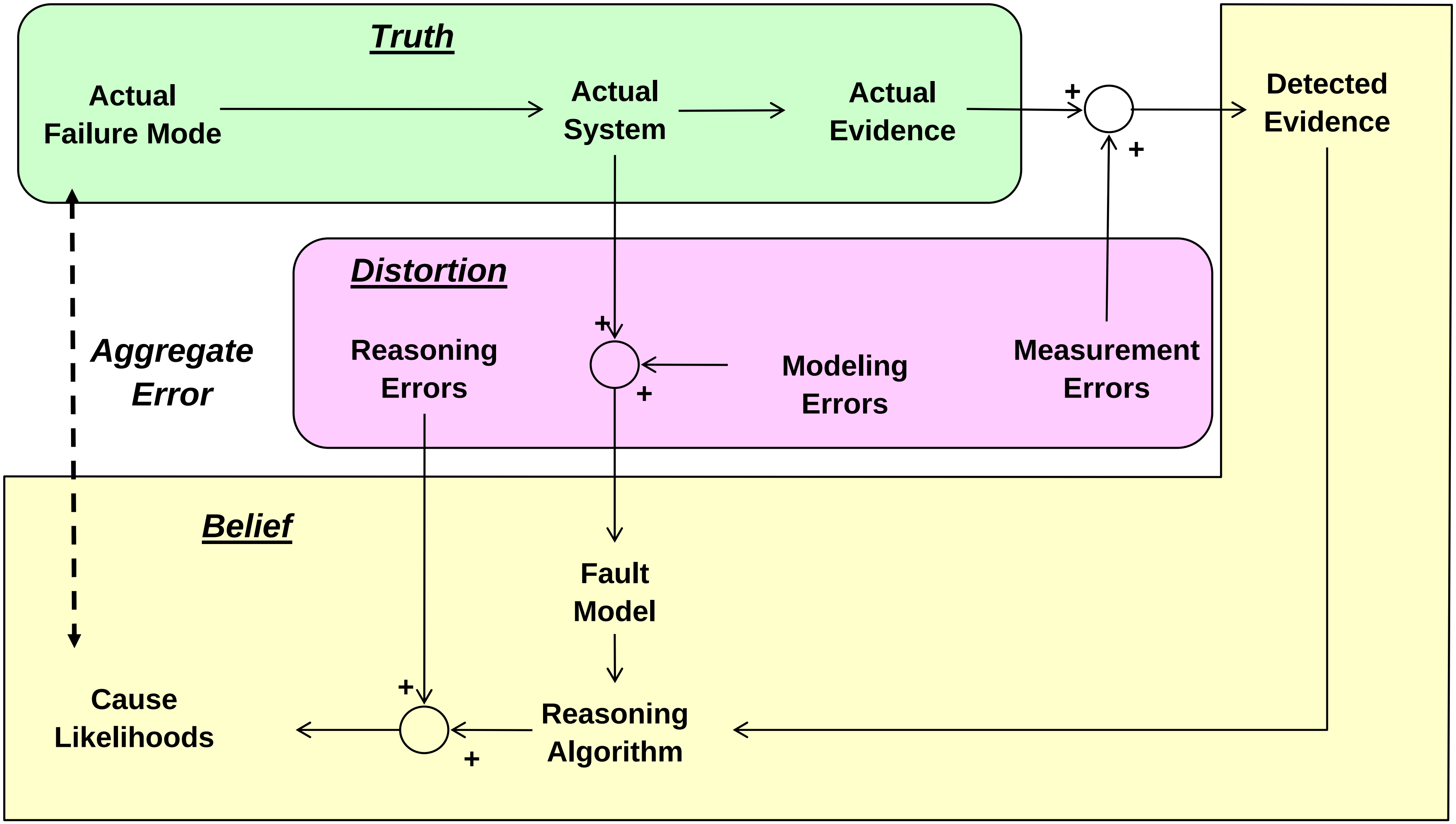

Evaluation of Accuracy

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- **Question: How can you evaluate the accuracy of a diagnostic result?**
  - **If the Cause Likelihood Vector for a specified set of evidence were:**
    - Dead Battery: .50
    - Faulty Wiring: .30
    - Controller Fault .20
  - **On what basis could you assess that these were the correct values or in error?**

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  - **On what basis could you assess that these were the correct values or in error?**

- **Answer 1: These likelihoods should be derived from the population of all simulated and/or real faults that produce all of the specified evidence (Correspondence).**

- **Answer 2: These likelihoods should represent the likelihood that the associated corrective action will in fact correct the defect (Effectiveness)**

- **Both answers are useful, but Answer 1 is more valuable since can be evaluated in advance of the deployment of the system.**

Diagnostics Based On Population Statistics

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The Exhaustive Form Fault Model is a complete listing of all fault events, their ultimate fix and the pattern of symptoms they produce.

	Test Cost		$0	$0	$0	$0	$56	$38		$9
Fault Event	Ultimate Fix	Repair Cost	Symptom 1	Symptom 2	Symptom 3	Symptom 4	Symptom 5	Symptom 6	...	Symptom k
Event 1	Cause 108	$240	X		X			X		
Event 2	Cause 76	$155		X	X					X
Event 3	Cause 3	$415	X		X			X		
Event 4	Cause 21	$212			X		X			
Event 5	Cause 27	$34	X				X			X
Event 6	Cause 59	$56		X	X		X			
Event 7	Cause 87	$122	X	X	X					
Event 8	Cause 45	$312	X	X	X					
Event 9	Cause 12	$78	X	X	X					
Event 10	Cause 108	$240	X					X		X
Event 11	Cause 34	$87		X	X			X		
Event 12	Cause 75	$189	X					X		X
Event 13	Cause 36	$13		X	X					X
Event 14	Cause 44	$43		X	X			X		
Event 15	Cause 108	$240	X		X					X
Event 16	Cause 69	$9					X			
Event 17	No Action Required	$0		X	X					X

This data can be produced two different ways:

a priori based on engineering data, simulations and test results

a posteriori based on data from actual fault events

(In this case, Corrective Actions will be known instead of causes)

Diagnostics Based On Population Statistics

- **Advantages:**
  - **The Exhaustive Form accurately encodes the full population statistics for a given set of binary symptoms and a given set of causes (or corrective actions) for a Level of Repair.**
  - **Using the Exhaustive Form, provably optimal algorithms can be established for the following diagnostic assessments:**
    - Likelihood of Each Candidate Repair (Cause) for a reported set of evidence (active and inactive symptoms)
    - Optimal repair sequence if no further evidence is available
    - Information value of symptoms whose state is not yet known
    - Dollar value of symptoms whose state is not yet known
    - Dollar value of additional symptoms that could be added to the model
    - Updates required to contents of the model based on newly observed syndrome / corrective action pair.
  - **The simple structure provides solid theoretical framework**

Fault Model – Combining Records

Records can be combined without loss of data:

	Test Cost		$0	$0	$0	$0	$56	$38		$9
Fault Event	Ultimate Fix	Repair Cost	Symptom 1	Symptom 2	Symptom 3	Symptom 4	Symptom 5	Symptom 6	…	Symptom k
Failure 1	Corrective Action 108	$240	X		X			X		
Failure 2	Corrective Action 76	$155		X	X					X
Failure 3	Corrective Action 3	$415	X		X			X		
Failure 4	Corrective Action 21	$212			X		X			
Failure 5	Corrective Action 27	$34	X				X			X
Failure 6	Corrective Action 59	$56		X	X		X			
Failure 7	Corrective Action 87	$122	X	X	X					
Failure 8	Corrective Action 45	$312	X	X	X					
Failure 9	Corrective Action 12	$78	X	X	X					
Failure 10	Corrective Action 108	$240	X					X		X
Failure 11	Corrective Action 34	$87		X	X			X		
Failure 12	Corrective Action 75	$189	X					X		X
Failure 13	Corrective Action 36	$13		X	X					X
Failure 14	Corrective Action 44	$43		X	X			X		
Failure 15	Corrective Action 108	$240	X		X					X
Failure 16	Corrective Action 69	$9					X			
Failure 17	No Action Required	$0		X	X					X
Failure 18	Corrective Action 1	$375	X		X		X	X		X
Failure 19	Corrective Action 172	$94			X					
Failure 20	Corrective Action 76	$155		X	X					
…	…									
Failure n	No Action Required	$0	X				X	X		

Fault Model – Combining Records

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Occurrence and Co-Occurrence Rates Encode Population Statistics:

Repair	Occurrences	Repair Cost	Symptom 1	Symptom 2	Symptom 3	Symptom 4	Symptom 5	Symptom 6	...	Symptom k
Corrective Action 108	3	$240	3		2			2		2
Corrective Action 76	3	$155		3	3					2
Corrective Action 3	1	$415	1		1			1		
Corrective Action 21	1	$212			1		1			
Corrective Action 27	1	$34	1				1			1
Corrective Action 59	1	$56		1	1		1			
Corrective Action 87	1	$122	1	1	1					
Corrective Action 45	1	$312	1	1	1					
Corrective Action 12	1	$78	1	1	1					
Corrective Action 34	1	$87		1	1			1		
Corrective Action 75	1	$189	1					1		1
Corrective Action 36	1	$13		1	1					1
Corrective Action 44	1	$43		1	1			1		
Corrective Action 69	1	$9					1			
Corrective Action 1	1	$375	1		1		1	1		1
Corrective Action 172	1	$94			1					
Corrective Action 76	1	$155		1	1					
No Action Required	2	$0	1	1	1		1	1		1

Cause Ranking Algorithms

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Population Statistics of Possible Causes

$$\text{Previous\_Cause}_i = \min(\forall \text{Evidence}_{j(\text{state} = \text{Present})}\{\text{CoOccur}(\text{Cause}_i, \text{Evidence}_j)\};$$
$$\forall \text{Evidence}_{k(\text{State} = \text{Absent})}\{(\text{Occur\_Cause}_i - \text{CoOccur}(\text{Cause}_i, \text{Evidence}_k)\})$$

Relative Likelihoods of Possible Causes

$$\text{Cause\_Likelihood}_i = \frac{\text{Previous\_Cause}_i}{\sum_{j=1}^{n\_Cause} \text{Previous\_Cause}_j}$$

Example Cases – Computing Cause Likelihoods

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	Previous	E1	E2	E3	E4	E5
C1	500	500				
C2	100	100	40			
C3	50	50	20	15		
C4	10	10	5	5	1	
C5	5	5	1	1	1	1

time1	E1 = P;	PrevC1 = 500,	PrevC2 = 100,	PrevC3 = 50,	PrevC4 = 10,	PrevC5 = 5
	E1 = P;	C_L1 = .75,	C_L2 = .15,	C_L3 = .075,	C_L4 = .015,	C_L5 = .007
time2	E1 = P, E2 = A	PrevC1 = 500,	PrevC2 = 60,	PrevC3 = 30,	PrevC4 = 5,	PrevC5 = 4
	E1 = P, E2 = A	C_L1 = .83,	C_L2 = .1,	C_L3 = .05,	C_L4 = .008,	C_L5 = .006
time3	E1 = P, E2 = A, E3 = P	PrevC1 = 0,	PrevC2 = 0,	PrevC3 = 15,	PrevC4 = 5,	PrevC5 = 1
	E1 = P, E2 = A, E3 = P	C_L1 = 0,	C_L2 = 0,	C_L3 = .71,	C_L4 = .23,	C_L5 = .02
time4	E1 = P, E2 = A , E3 = P, E4 = P	PrevC1 = 0,	PrevC2 = 0,	PrevC3 = 0,	PrevC4 = 1,	PrevC5 = 1
	E1 = P, E2 = A , E3 = P, E4 = P	C_L1 = 0,	C_L2 = 0,	C_L3 = 0,	C_L4 = .5,	C_L5 = .5
time5	E1 = P, E2 = A , E3 = P, E4 = P, E5 = P	PrevC1 = 0,	PrevC2 = 0,	PrevC3 = 0,	PrevC4 = 0,	PrevC5 = 1
	E1 = P, E2 = A , E3 = P, E4 = P, , E5 = P	C_L1 = 0,	C_L2 = 0,	C_L3 = 0,	C_L4 = 0,	C_L5 = 1

Identifying Fault Condition Boundaries

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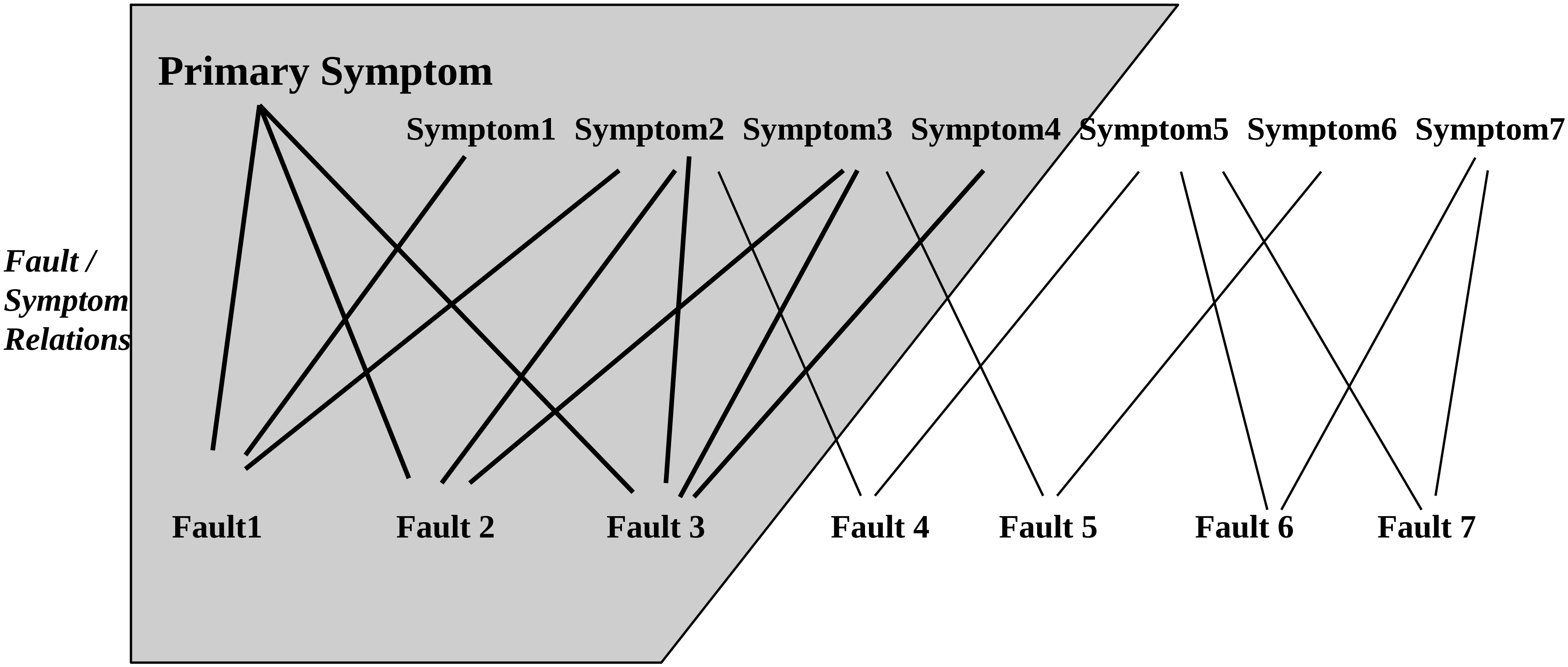

Fault Condition Boundaries Allow the System to Handle Simultaneous Failures.

The Honeywell Fault Model

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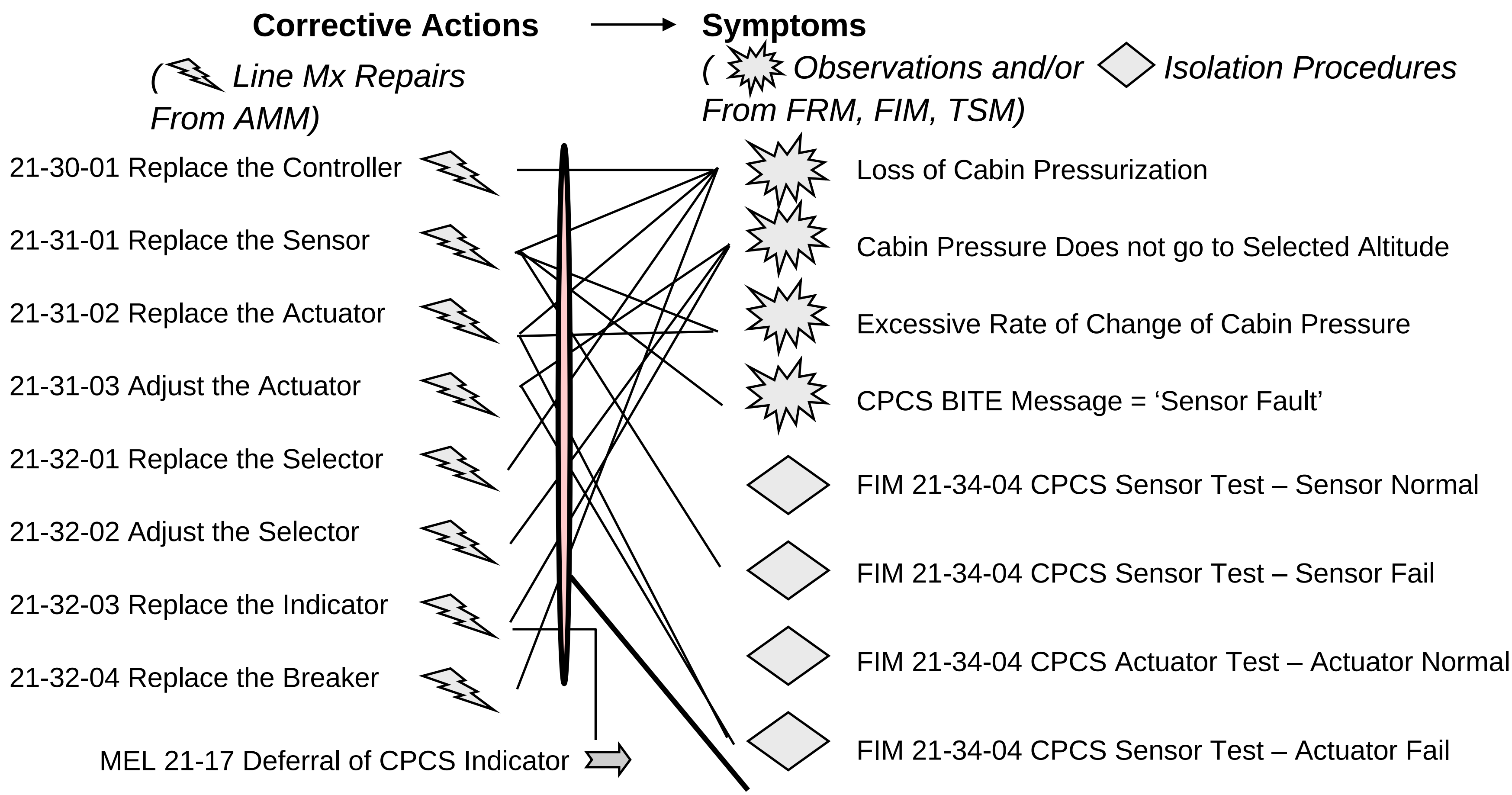
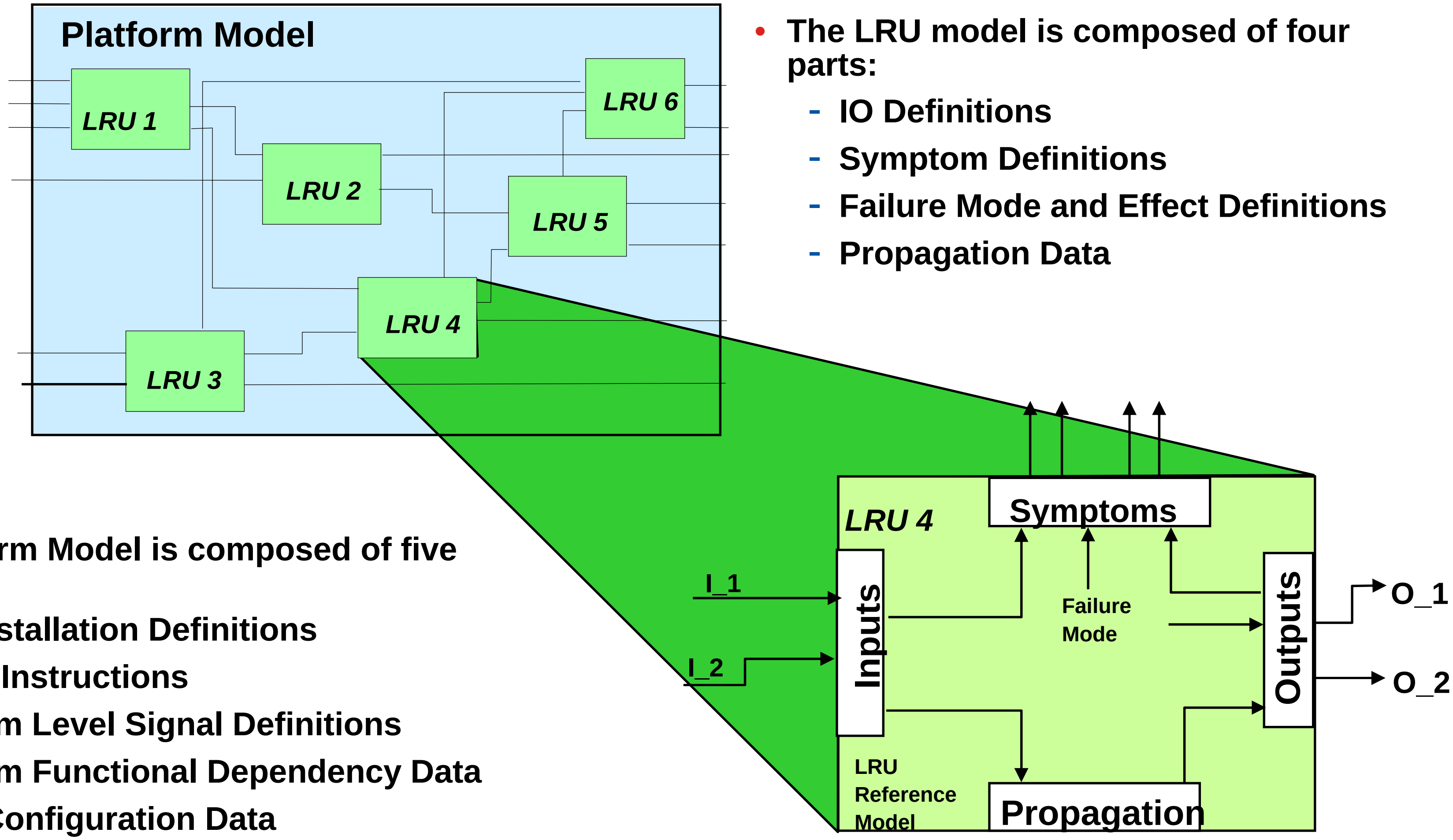


Relationships encode logical and quantitative information.

The Honeywell Fault Model is a greatly compressed version of the exhaustive model that is structured to prevent distortion or loss.

Hierarchical Fault Model (Connectivity Based)



- The LRU model is composed of four parts:
  - IO Definitions
  - Symptom Definitions
  - Failure Mode and Effect Definitions
  - Propagation Data

- The Platform Model is composed of five parts:
  - LRU Installation Definitions
  - Repair Instructions
  - Platform Level Signal Definitions
  - Platform Functional Dependency Data
  - IVHM Configuration Data
    - Data Collection Rules
    - Inhibit Data
    - Calculated Cascade Data
    - Calculated Time Delay Data

Fault Model Overview

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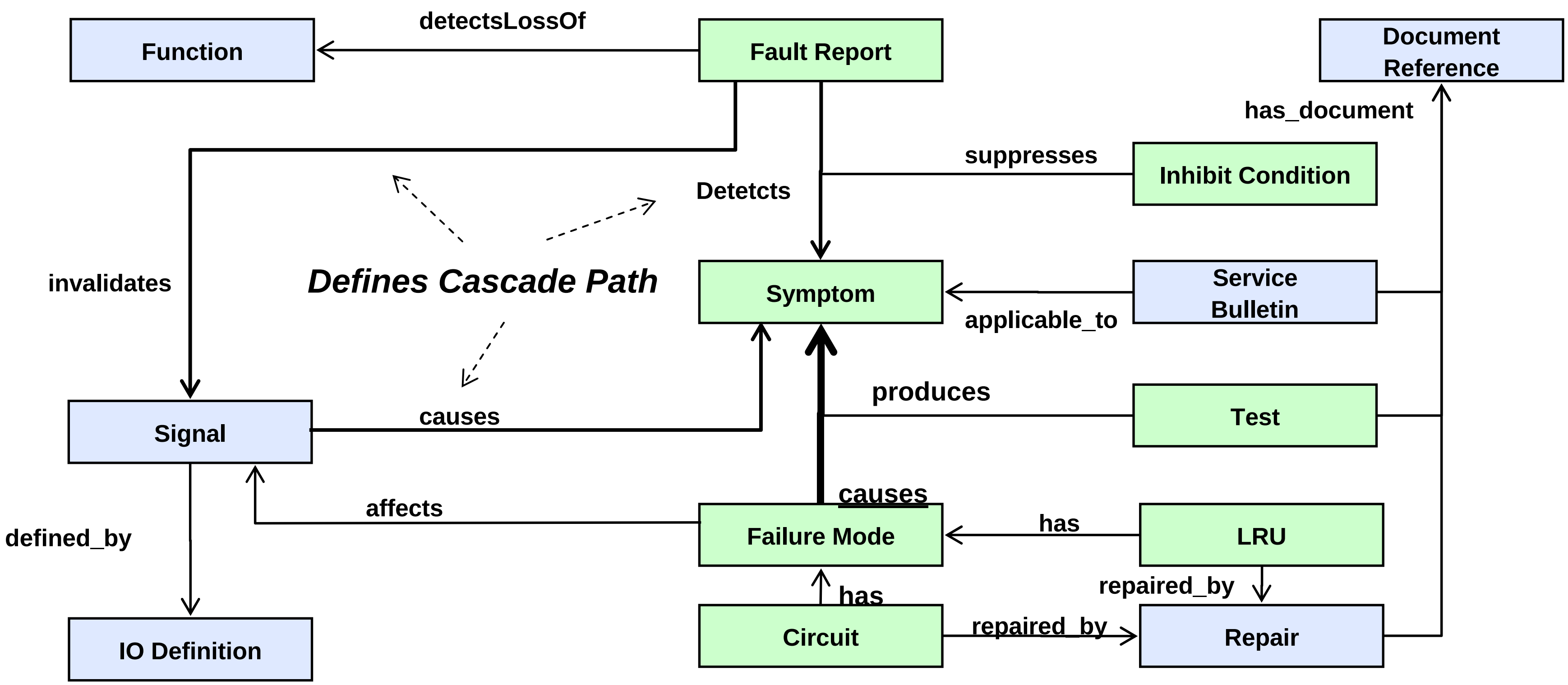

The fault model must be built and maintained through a rigorous knowledge management process.

Experience From 777 and 787 Central Maintenance Computer Development

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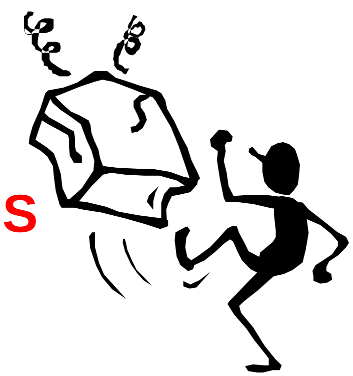
Maintenance System Lessons Learned *(pre-Boeing 777)*

- **Earlier Maintenance Systems suffered from:**
  - **Poor Correlation between Pilot Observations and required Mechanic Actions**
  - **Human Usage Scenarios not adequately addressed**
  - **False, Misleading and Ambiguous Nuisance Messages**
  - **Lack of Built-In Test (BIT) consistency among Subsystems**
  - **Poor Handling of Power Transient Response**
  - **Optional Equipment not covered by Maintenance System**
  - **Slow turnaround of software rule updates did not keep up with aircraft design changes**
  - **Poor visibility into effects caused by software rule updates**

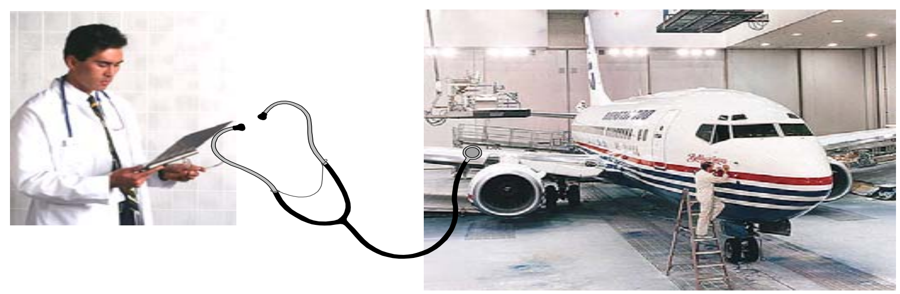
NUMEROUS SYSTEM INTEGRATION PROBLEMS



CMC Serves as an 'Airplane Doctor'

- Boeing 777 introduced the CMC fault-model approach
- CMC Monitors all aircraft Member Systems
  - Continually collects symptoms, during flight, from all the avionics boxes on the airplane
  - Diagnoses the real fault (i.e., the root cause) behind the symptoms
  - Correlates the fault with flight crew observations (alerts)
  - Informs the maintenance crew of the required repair action

Nearly all of the CMC functionality is controlled by the Fault Model!!!



- **Data Driven Functions Include:**
  - **I/O, Nuisance Suppression, Inhibit Processing, Time Delay Processing, Cascade Removal, Consolidation, FDE Correlation, Maintenance Message Displays, Initiated Test Displays, Configuration Reporting**

Rule-Based versus Model-Based

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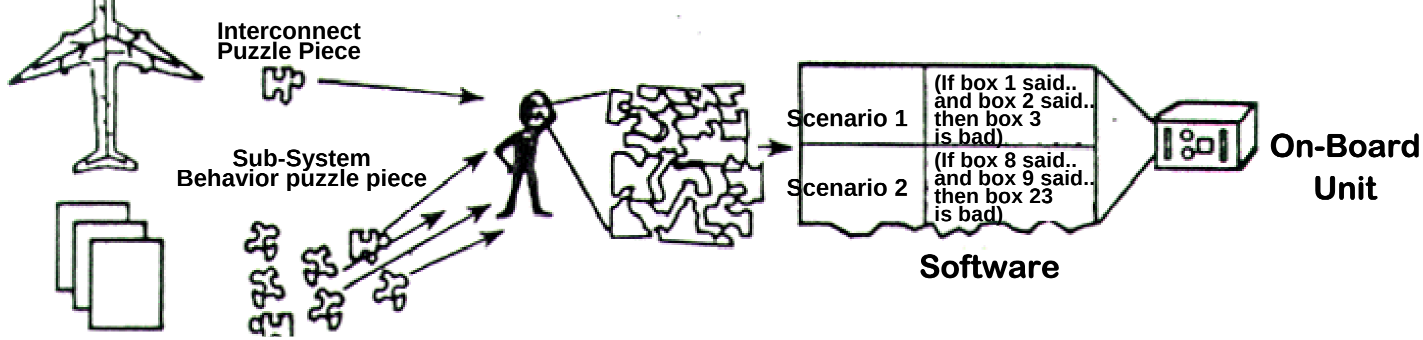
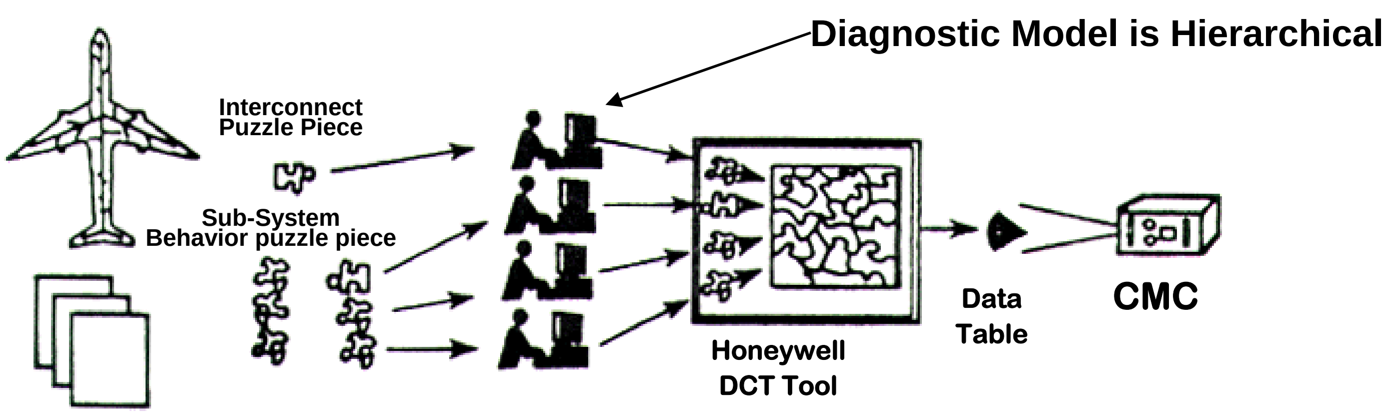
Previous Rule-Based Approach

Expert System Engineer is asked to diagnose faulty LRU for thousands of symptom scenarios



Honeywell's Model-Based Approach



- Each expert is asked to describe only his/her subsystem behavior
- Honeywell modeling tool fits the pieces together and generates a data table
- The data table is used by the CMC software to diagnose failures

Knowledge Management Approach to 777 CMC

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Problem Statement

- Provide tools and processes to allow each of 100 system suppliers to model the failure modes, functional effects and detected symptoms for their portion of the aircraft
- Provide tools and processes to allow Boeing to integrate all models into comprehensive, aircraft level model.
- Model structure must account for all variations in interconnections between systems and for variations in ways that systems reported symptoms to the CMC
- Model structure must provide economic solution to the problem of modeling redundant systems (since 90% of model content is the same between all installations of the redundant components).
- Model structure must capture all data needed to support all of the functionality of the CMC

Knowledge Management Approach to 777 CMC

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- **Failed Attempts**
  - **Object Oriented Database**
    - Analysis of the problem indicated that there would be a substantial difficulty in calculating the cascade chains, which were expected to include 100,000's of links, in a reasonable time if we used a relational database.
    - This approach failed due to the embryonic state of Object Database technology in the early 1990's.
  - **Centralized Relational Database**
    - A solution was found to the cascade calculation problem and the design was switched to a centralized relational database.
    - This solution was found to be unworkable due to the fact that the high degree of evolution that was required for the application was not compatible with the IT overhead of developing, validating, securing and supporting the centralized system.
- **Final Solution**
  - **Distributed Desktop Application Controlled by Meta-Data**
    - A tiger team was established to find solution and they developed a lightweight, highly configurable desktop database application to edit and integrate the models
    - Configuration was controlled through application meta-data that specified the structure of the fault model data, the workflow for its construction and the consistency checks that should be applied at each step.
    - Updates to the meta-data could be distributed to all suppliers who could apply the changes to their installation.
    - Changes that had previously taken many weeks to implement could now be made and distributed in a few days.

Aerospace Fault Model Development Process

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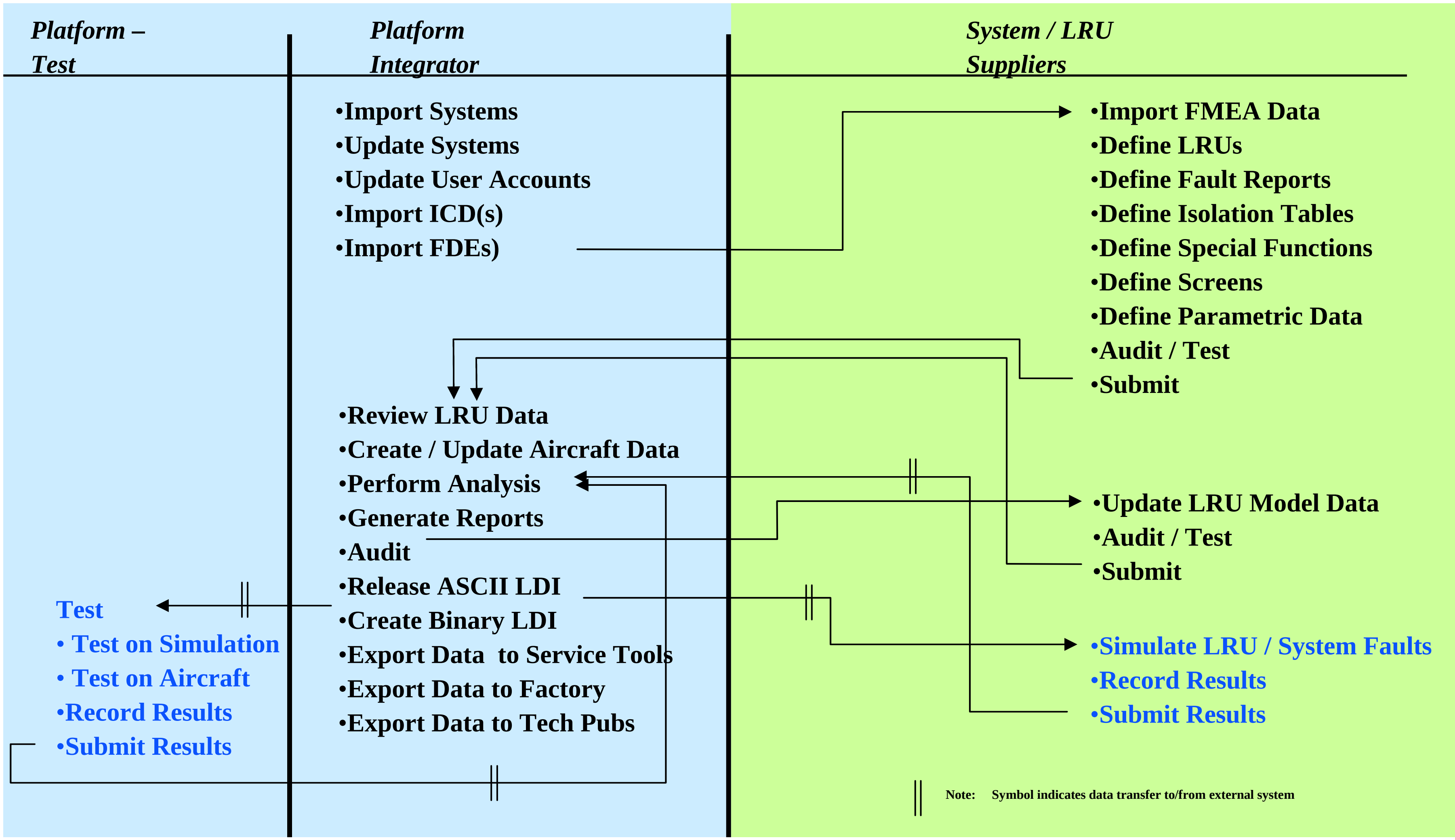

Knowledge Management Approach to 777 CMC

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- **Lessons Learned**
  - Over reliance on cutting edge technology can lead to unmanageable risks.
  - For this application, fast, reliable response to evolving requirements was the most critical factor leading to success.
  - Efficient modeling of redundant systems was a technically challenging but critical aspect of the design.
  - Change control and configuration management of the model elements, which was barely even a requirement at the beginning of the project, became a major element of the final system.
  - The user community came to depend on a wide variety of user definable analyses and reports to validate and troubleshoot problems in the their models.
  - Workflow, consistency checks and task based editors were identified as a major area for future improvement and were included in the system provided to Boeing for the 787 aircraft.

Knowledge Management Systems for Condition Based Maintenance (CBM)

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- **Key Capabilities of Current & Future Generation Systems**
  - **Management of information model via meta-data**
    - A Single, declarative model of information to be captured and associated processes should control all aspects of KMS functionality (e.g. database schema, user interface, user manual / training and help files, data import and export, consistency checking, analysis, reports, data output generation.
  - **Import and Conversion of Data from Various Sources**
    - The system should be able to import data from Historic Records, Existing Maintenance Manuals and Engineering Design Data.and convert into useable fault model content.
  - **Support of Re-Use of System and LRU Models**
    - System Models must be constructed to allow their re-use in multiple locations on a single platform or on many different platforms
  - **Change Control and Configuration Management**
    - The system must provide robust tools and processes to control and track change to the model content.

Fault Model Development Considerations

- Fault Model Tools must provide the following functions:
  - Allow import or authoring of hierarchy of platform
  - Provide tools to import of wide variety of existing data
  - Provide tools to scrub imported data and relationships
  - Provide tools to author new data and relationships
  - Allow models to be developed for LRUs, Systems or Platforms
  - Allow LRU models to be re-used on multiple Systems
  - Provide admin functions to allow different portions of the model to be viewed and updated by different suppliers.
  - Allow System models to be used on multiple Platforms
  - Provide tools for versioning and configuration management
  - Provide tools for analysis and reports
  - Provide tools to create on-board database that is optimized for size and performance

Knowledge Management Tools Allow Integrator to Overcome Fundamental Complexity of Task

CBM Knowledge Management Lifecycle Phases

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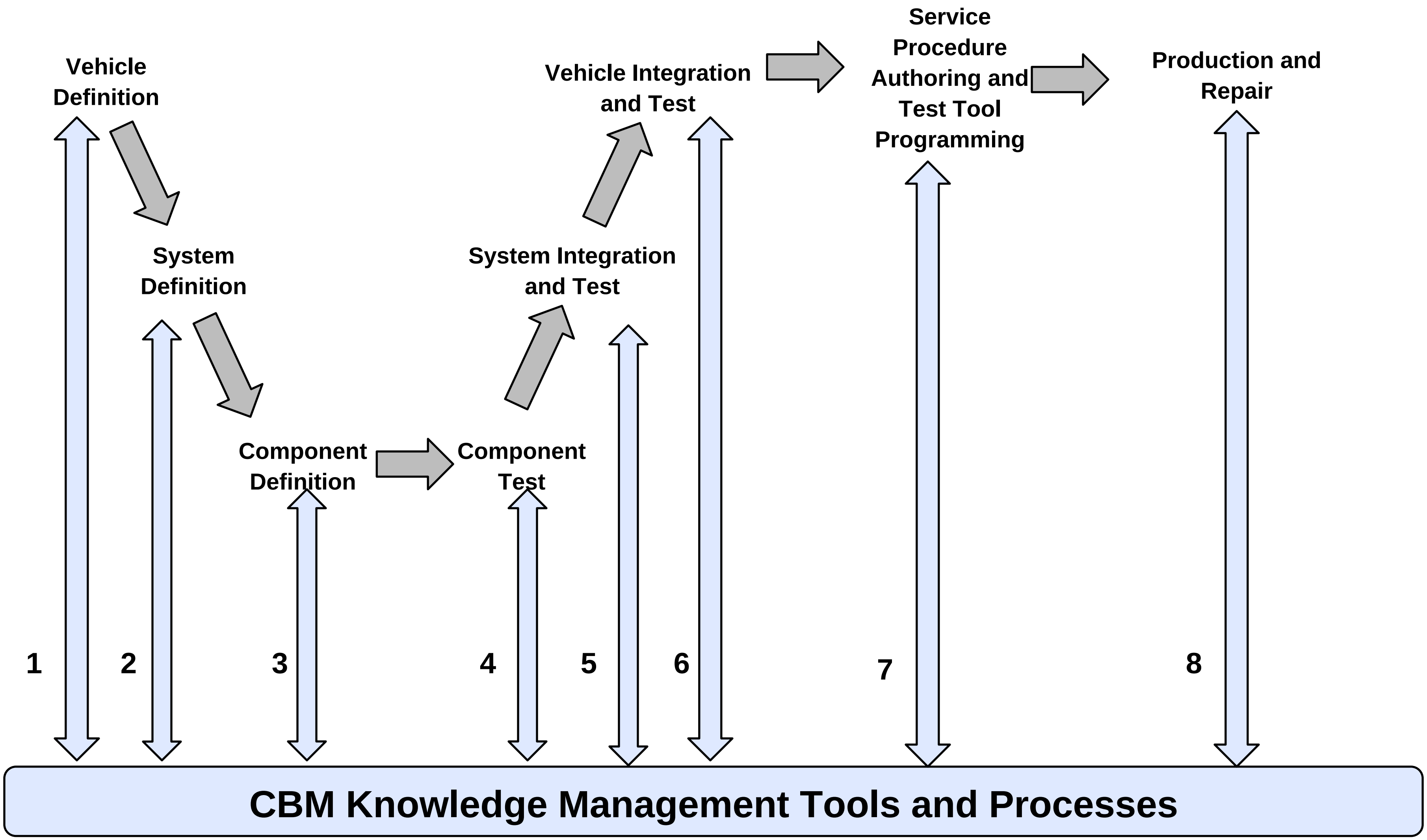

Summary

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- Population statistics of failure modes and the rates at which they produce symptoms (simulated or real) can be used to evaluate the accuracy of diagnostic algorithms and fault models.
- Construction of a fault model can be decomposed by modeling failure mode and effect data for each element and the connections between elements.
- Tools are needed to support the development of fault models.
- The features of these tools and the rate at which they can be adapted are critical to the success of a diagnostic program.