the New Science of FIXING THINGS

Summary of Concepts in Performance and Reliability Diagnosis

Concept	Summary
• **Purpose of Systems**	• Systems process signals, matter and energy; behavioral performance is defined for these as outputs.
• **Nature of System Throughputs**	• Signals are energy and can also be matter. Properties common to all system behavior determine signal transmission / reception performance.
• **Definition of a Problem**	• A problem is a situation bearing improvement. A problematic phenomenon is a discrepancy in intended behavior.
• **Fault-Observation Proximity**	• Diagnosis is greatly simplified the closer the observation is to the faulty system element,
• **Fault-Observation Signal Transformations**	• Diagnosis is greatly simplified with fewer signal transformations between performance and observation.
• **Search Strategy**	• Any diagnostic search that uses a hierarchical process of elimination is based upon consistency between suspects and observations.
• **Case** vs **Model-Based Reasoning**	• Reasoning about consistency can be case-based (symptomatic) using a compilation of cause-effect relationships built up experientially, or model-based (topographic).
• **Model Representations**	• Topographic reasoning derives an explanation of behavior from a representation of knowledge about a system's elements and their interrelationships.
• **Logic of Model-Based Reasoning**	• Topographic reasoning involves three types of logic:
• **Abduction**	• Abductive – decomposing the system into viable hypotheses using some model
• **Deduction**	• Deductive – diagnostic search by constraint satisfaction – evaluating and refining hypotheses
• **Induction**	• Induction – adopting one hypothesis based on empirical evidence.
• **Nature of System Outputs**	• Work and heat are transitory energy, so useful work is a useful transition of energy and sometimes also of matter.
• **Correlations Between System Throughputs**	• A transition of matter is always accompanied by a transition of energy.

• **Diagnosis and Performance Characterization**	• We can <u>often</u> diagnose system performance from a characterization of signals, matter, properties and geometries, but we can <u>always</u> diagnose by characterizing performance in terms of energetic interactions.
• **Limitations of Alternative Performance Characterizations**	• Non-energetic characterizations put a limit on the lowest level of system decomposition that can be discriminated.
• **Nature of System Elements**	• System elements that govern performance are properties and geometries.
• **Function of Surfaces**	• Surfaces are an interface between different properties.
• **Use of Geometry**	• Geometries are a special sub-set of properties that characterize surfaces.
• **Properties Governing System Behavior**	• The properties that drive system behavior are resistance, inertance and compliance, which combined result in impedance.
• **Hierarchical Characterization**	• Resistance, inertance and compliance can be characterized hierarchically in any system.
• **Use of Comparative Analysis**	• Comparative analysis is useful for diagnosing variation if it is tactically expedient to do so, but energy-based decomposition is often faster.
• **Leverageable Axioms of Comparative Analysis**	• Comparative analysis can exploit the combination of Pareto and Root-Sum-Squares
• **Need for Statistically Designed Experiments**	• The logic of induction requires that a hypothesized causal explanation is tested in such a way that the risk of false conclusion is acceptable. Proper experimental design manages this risk. During the diagnostic search, this risk is not important, but the risk of eliminating contributing factors is.
• **Definition of Structural Models**	• A structural model describes what a system is made of, and/or what it is made by.
• **Definition of Functional Models**	• A functional model describes the means-to-an-end (How-Why) relationships for achieving a goal.
• **Use of Comparative Structural Decomposition**	• If different systems vary in output performance, we can decompose them structurally, but only comparatively between at least one pair of similar units, and only to the lowest structural elements.

• **Structural** vs **Functional Observability**	• Observability is fundamental to successful diagnosis. It is usually easier to test the nodes (functions) of a functional model than any sort of structural model.
• **Comparative Functional Decomposition**	• If the output of one system varies, we can decompose functionally based on comparative analysis of those outputs to explain the variation.
• **Isolation Tactics for Diagnosis by Functional Decomposition**	• The strategy of Isolation is to decompose the system into inputs, function and interdependency between input & function. Different tactics are appropriate to the conditions of a specific case.
• **Reversibility and Non-Reversibility**	• Reversible functions are common in manufacturing systems – many assembly and measurement processes can be reversed and repeated on the same set of inputs. If this is not possible, the function is non-reversible.
• **Repeatability**	• Reversible functions can be decomposed by testing several inputs twice, or two inputs several times.
• **Spatial Manipulation**	• When the output of non-reversible functions displays spatial non-randomness, they can be decomposed by careful spatial manipulation of either input or functional elements.
• **Temporal Manipulation**	• When the output of non-reversible functions displays temporal non-randomness, they can be decomposed by careful temporal manipulation of either input or functional elements.
• **Replication**	• Parallel (or quasi-parallel) inputs are easily separated to decompose the system into inputs, function and interdependency between input & function.
• **By-Pass**	• Certain functions can be by-passed between input and output to test their effect, rather than their functionality.
• **Correlation**	• This requires much care in planning the execution – couple with other tests of consistency, or other Isolation tactics. Forensic evidence is a powerful means of decomposing the system.

- **Dissection Tactics for Diagnosis by Structural Decomposition**
  - Dissection can be expedient for decomposing parallel and quasi-parallel systems. Cannot be performed without prior knowledge of repeatability of reversible functions performed during data acquisition.
  - **Strengths**
    - Dissection is capable of quantifying interdependencies between structural elements that are functionally related.
  - **Half-Split**
    - The Half-Split Dissection is the simplest structural decomposition into two sub-groups and interdependencies.
  - **Search**
    - Search Dissection can improve efficiency by decomposing into more sub-groups, but the gains rapidly reduce with more than five.
  - **Limitation of Structural Decomposition**
    - Explanation of behavior cannot be structural.
- **Matryoshka Tactics for Diagnosis by Structural and Functional Decomposition**
  - The strategy of Matryoshka is to undertake comparative analysis simultaneously at multiple levels of decomposition. Comparison is made between strength of contrasts level to level, and suspect consistency is checked across all levels.
  - **Functional Hierarchy**
    - Sequential, reversible functions can be treated as multiple levels of decomposition. Repeatability of the last function in a sequence is nested inside repeatability of the next from last, and so on.
  - **Structural Hierarchy**
    - Contrasts exist between quasi-parallel structural elements at multiple levels of decomposition. For geometric elements, nesting dimensional data for a datum to a surface allows size and shape to be characterized in one graphic (see small multiples under tools).

- **Tools for Comparative Analysis**
  - Improve deduction through revelation of the complex, not complication of the simple. Graphical representation allows rapid assimilation and comprehension of large amounts of data by humans. There are five basic graphic types.
- **Time-Series**
  - Time series plots compare each reported value to the rest, in sequence. Correct interpretation of data is sensitive to choice of intervals, and suffers from the weakness that chronology is not a causal explanation.
  - **Cumulative Time-Series**
    - Using very small time intervals and cumulative presentation of data readily reveals changes that are otherwise masked.
- **Data Map**
  - Data maps are sometimes called concentration plots or Picasso plots. They relate locations and event occurrences to see concentration patterns.
  - **Polar Plot**
    - Polar Plots are Data maps suited to circular geometry. Powerful for visualizing patterns in vector/phasor to angle relationships.
- **Distribution Plot**
  - Distribution plots relate proportions of populations to a single variable and are primarily used for summarizing.
  - **Histogram**
    - Histograms can be used qualitatively as a graphical description of distribution of data without recourse to a mathematical model.
  - **Cumulative Distribution**
    - Cumulative plots of distributions are sensitive to changes in probability density.
- **Paired Data**
  - Paired Data plots show dependence/independence between sets of associated values, the range in both x and y directions, and concentrations of results.
  - **Scatter Plot**
    - Scatter plots are often used qualitatively with curves showing X-Y relationships.
  - **Youden Plot**
    - Youden plots are differ from scatter plots although superficially they appear the same.
- **Small Multiples**
  - Small Multiples are repeated examples or combinations of time-series plots, data maps, histograms and paired data plots. Particularly suited to Matryoshka tactics.
  - **Multivari**
    - The Multivari chart is a small-multiple that is a compact graphical format useful for comparing contrasts.

• **Value of Variation Reduction**	• Diagnosing system performance variation allows us to refine our system design and reduce it by reducing variation in properties and/or geometries.
• **Limitation of Variation Reduction**	• Reducing variation is not always the best course of action.
• **Overcoming Limitations of Variation Reduction**	• Greater improvement than those of refinement require redesign or re-engineering. A full explanation of system behavior that must include energy supply, distribution, storage and dissipation, is required to undertake redesign and re-engineering.
• **Overcoming Limitations of Comparative Analysis**	• Decomposing a system functionally can be undertaken without comparison between units and continued to the lowest level.
• **Definition of Re-design**	• Re-design involves modifying resistance and/or inertance and/or compliance to reduce parasitic losses/degradation and improve function of all units.
• **Definition of Re-engineering**	• Re-engineering involves fundamentally adding or removing functions performed by or within a system.
• **Iterative Product Development**	

- **Energetic Model Building Blocks** — Seven functions, related to the three properties resistance, inertance and compliance, describe all system behavior.
- **Physical Axioms** — These functions are based on the following axioms of physics, which provide invaluable insight into system behavior:
  - **Multi-Domain** — Energy interacts through multiple domains; mechanical translational, mechanical rotational, electrical, magnetic, hydraulic, thermal and chemical and others.
  - **Traceability** — Energy interactions are easily traced across domains.
  - **Conjugate Variables** — Power decomposes into effort (across) and flow (through) conjugate variables in every domain.
  - **Energy and Power Relationships** — Storage integrates one of the power conjugates with respect to time to derive energy quantities; either flow is integrated for potential energy, or effort is integrated for kinetic energy.
  - **Importance of Causality** — A power source determines the amount of effort, in which case the sink determines the amount of flow, or vice-versa.
  - **Cross-Domain Kirchoff Laws** — When power is transmitted, the function is either to divide effort or divide flow.
  - **Dissipation Causality** — Power dissipation passively determines effort or flow depending upon what the other system elements; storage, source, distribution, dictate.
  - **Conversion** — Conversion describes the change in leverage between effort and flow, as in the transformation of torque and speed through a gear ratio. It may also change domain and/or reverse causality between effort and flow.
- **Characterization Using Energy** — Power and energy conjugates in different domains fully characterize system performance.
- **Improving Observability** — Alternative (partial, inexact or indirect) observations which can decisively test the state of many functions to avoid time and resource-consuming tests are identifiable in energy-based functional models (E-FAST).

- **Efficiency of Functional Searches**
  - Functional models improve diagnostic efficiency by focusing testing only on those functions capable of contributing to higher level misbehaving function or performance.
- **Insights from E-FAST**
  - Energy-based functional models represent multi-domain circuit diagrams, annotated to show causality and division of effort/flow.
- **Developing Search Tactics from E-FAST**
  - Energy-based functional models facilitate the verification of functionality by tactics such as short-circuiting; changing resistances, compliances or inertances; probing effort and flow at nodes; and increasing or decreasing effort or flow as appropriate.
- **Tactics for Intermittent Faults**
  - One characteristic of intermittent functionality is that it occurs when dissipated power and supplied power are approximately equal. Reduce supplied power to verify functions.
- **Extending from Performance to Reliability**
  - Degradation is changes to resistance and compliance over time.
- **Nature of Hard Failures**
  - So-called hard failures occur when either:
  - **Overload**
    - Compliance limits are exceeded (trying to cram in more potential energy than an element is capable of containing), or
  - **High Resistance**
    - Resistance requires more effort or flow than is available.
- **Leveragability of Functional Models**
  - Functional models greatly enhance knowledge acquisition and are re-usable for large families of devices that share common functionality.
- **Building a Knowledge Base**
  - Functional models can be enriched with knowledge to aid diagnostics; observable properties, including the partial, inexact, indirect and side-effects.