Complexity, Robustness and Sociotechnical Systems Modeling

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Outline of Workshop

- What is the System? (20-30 min)
  - Barrett start, Kris handoff
- Systemic Failures and Robustness (30 min)
  - Kris continue, Barrett return
- 5-10 Minute Break
- What do we do about it? (20-90 min)
  - 15 min Barrett and Kris
  - (After lunch): Barrett leads discussion

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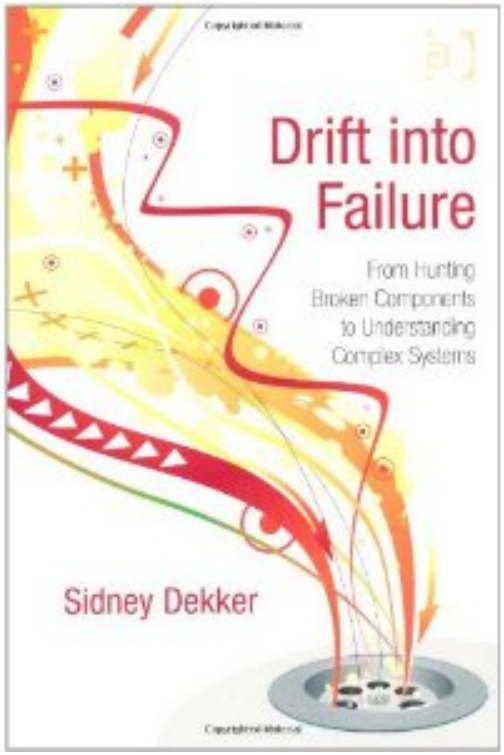
Workshop Materials

- Slide Handouts
- Informal Lecture Notes
  - Details beyond slides
- Reference Text
  - Sidney Dekker, *Drift into Failure*, 2011



Barrett Presentation Overview: What is the System?

- Two Introductory Examples
- Flavors of Systems Engineering
- Dekker Discussion: Newton, Descartes, Nietzsche
- Considerations of Dynamics and Experience
- Handoff to Venkat

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What is the System? Example 1

- Proposed NASA Mission?
  - (Supposed to be Funny: The Onion)
    - Definitions and Goals
    - What is Context?
    - Boundaries and Constraints
    - Inputs, Outputs, Transformations
    - Environmental Influences
    - Searching for Success
- This Can Be Done Anywhere

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What is the System? Example 2

- Designers: Groups of 2-3
- Goal: Plan a Barbecue for Next Weekend
  - 25 guests
  - Guests arrive hungry, leave full
  - Fun is an implicit measure of goal achievement
- Environmental Context / Condition
  - Local municipal park
  - No food preparation equipment, but tables and benches

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Which of the Following Are Relevant Factors Influencing System Design and Performance?

- Hygiene and Food Preparation History in Fertile Crescent and Northern Africa
- Earth Axis Tilt
- Religious Philosophies of the Indus Valley and US Rocky Mountains
- Heat Capacities of Stainless Steels

- Why?

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Flavors of Systems Engineering

- "Systems Thinking"
  - Feedback, flows, and loops
  - Gleick, Meadows, Senge
- "System Dynamics"
  - Equilibria and energies in biological and other contexts
  - Von Bertalanffy, Weiner
- "Components and Integration"
  - Component designs, engineering controls
  - Blanchard, Sage
- "Process Management"
  - Milestones, resource allocations, schedules
  - Buede, Gantt

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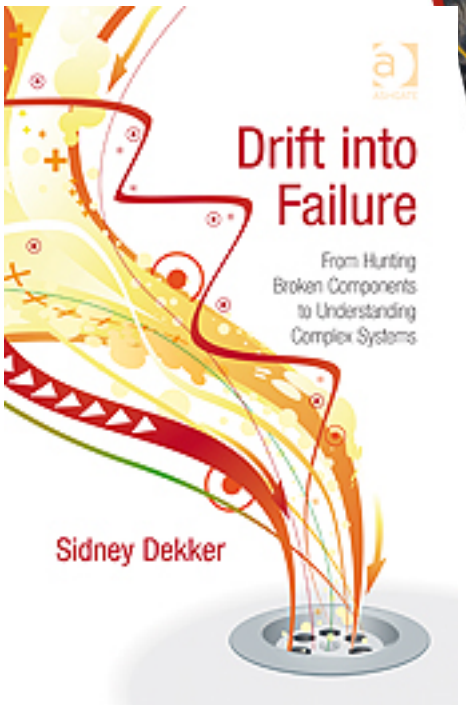
A Philosophical Discussion of Robustness Approaches

- Sidney Dekker, *Drift into Failure*
  - Reading, not textbook
  - Perspectives, not prescriptions



- Considering multiple approaches
- Discussing other worldviews

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Dekker's Challenge

- Engineering System Design, Integration and Performance is Legacy of Newtonian World
- Systems Engineering Approaches Above Have Limited Application
  - Complexity of Interactions
  - Sociotechnical Operations
  - Conflicting, Imperfect Information
- System Analysis and Cause / Effect Based on Logic (Decartes)
- Limited Application to Modern Technologies

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Why Discuss Nietzsche?

- Alternative Viewpoint on Sociotechnical Engineering Performance and Adverse Events
  - I'm reporting, not assuming or convincing
- Actual State of System Depends on Local Viewpoints, not Absolute Knowledge
- Full Complexity Is Not Knowable
- Adverse Events Comforting to Attribute to Evil or Demonizing, but Less Accurate

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Human Error Taxonomies

- Ways to Describe Problems in Performance
- Getting at Sources of Problem—Grain Size Required for Improvement
- Started as Ways to Determine How Operators Messed Up
- Earliest: Swain's THERP
  - Omission: Didn't do what you were supposed to
  - Commission: Did something you weren't supposed to
  - Sequence: Did it in the wrong order
  - Timing: Did it at the wrong time
- Not Always Helpful, Other Theories Developed

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An Intro to Stages of (Individual) Human Performance

- Getting Information about the World
  - Signal ***Detection***
- Processing Meaning and Linking to Prior Experience
  - ***Interpretation***, Sensemaking, Encoding, Working Memory
- Determining What to Do about It…
- Existing Ways to Perform, Memory for Rules
  - Rule ***Retrieval*** and Structure
- Non-Standard Ways to Perform, Choosing Desired Outcome
  - Strategic ***Planning*** and Creative Resolution
- Doing the Performance
  - Task ***Execution***

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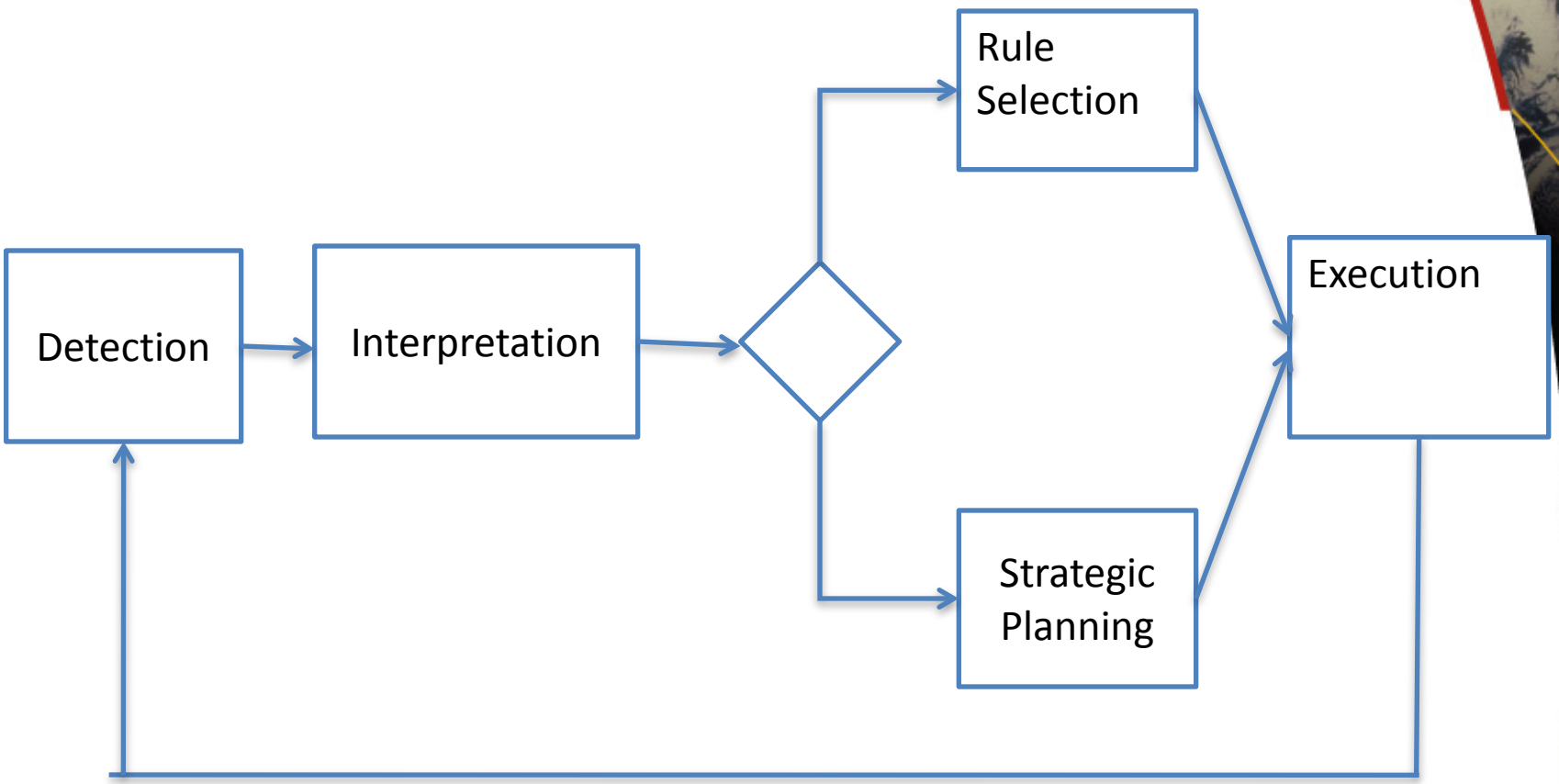
Flow of (Individual) Human Performance Stages



Examples of Error Taxonomies

- Rasmussen: Skill, Rule, Knowledge
  - Skill: Execution problems with physical actions—***well trained?***
  - Rule: Memory of established procedures and which one to retrieve—***well learned?***
  - Knowledge: Ability to resolve and strategically plan according to situation complexity—***well understood?***
  - Focus on Physical, Operational, Strategic Phases
    - Details of SRK may not be correct (Caldwell)
    - Important distinctions—not all performance equal

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Examples of Error Taxonomies

- Reason: Slips, Lapses, Mistakes
  - ***Slip:*** Correct intention, physical execution problem
  - ***Lapse:*** Memory retrieval problem
  - ***Mistake:*** Task choice problem based on improper understanding or interpretation of situation
  - VIOLATIONS ARE DIFFERENT
    - Intention to do something other than rules specify
    - Noncompliance—desire to do something else
      - Appropriate: rules as specified won't work
      - Inappropriate: rules do work, person is introducing problems

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Importance of Reason Approach

- Multiple Types of Causal Impacts
- Single Errors Rarely Cause Catastrophic Effects
- Change in Grain Size
  - Team coordination and handoffs
  - Processes of recovery and organizational response
- Impacts on GROUPER Medical Event Reporting System Approach

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Handoff to Venkat via Kris

BP Oil Spill 2010

BP Texas City 2005

Flixborough 1974

Systemic Failures:
Risk Management in Complex Systems

Northeast Blackout 2003

Lehman Bros 2009

Sub Prime Global

ENRON 2001

Systemic Failures Across Industries

- Chemical
  - BP Oil Spill (2010): Off-shore oil platform
  - BP Texas City (2005): Explosion in isomerization unit
  - Exxon Valdez (1989): Oil tanker accident
  - Piper Alpha (1988): Off-shore oil platform
  - Bhopal Gas Tragedy (1984): Methyl isocyanate leak at Union Carbide plant (worst ever industrial disaster)
- Electrical
  - Northeast Power Outage (2008): 10 M in Ontario, 45 M in US

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Systemic Failures Across Industries

- Mining
  - Massey Energy (2010): West Virginia mine disaster, 29 killed
- Pharmaceutical
  - Schering Plough Inhalers Recall (2002): 59 M inhalers
- Societal
  - Collapse of Mayan Civilization (~800-900 CE): environmental / societal collapse?
  - Collapse of Easter Island Civilization (~1500 CE): environmental / societal collapse?

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Systemic Failures Across Industries

- Financial
  - Madoff scandal (2008-09): Ponzi scheme: $65 B losses
  - Subprime mortgage (2007-08): $ xx T in losses, government rescues
  - Lehman Bros. (2008-09): Collapse of Wall St. firm, 26K employees lost jobs
  - WorldCom (2002): Accounting fraud, $180 B lost, 57K employees lost jobs
  - Enron (2001): Fraud through off-books partnerships, $60 B lost, 20K employees lost jobs
  - Savings & Loan (1980s): deregulation and real estate speculation, ~1000 S&L failures, $160 B lost

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Chemical	*BP Oil Spill (2010):* Off-shore oil platform explosion leading a large oil spill 11 people killed; > $20 bilion losses; incalculable damage to the environment
	*BP Texas City (2005):*Explosion in the isomerization unit; 15 people killed; ~180 people injured; $10 billion law suit pending
	Exxon Valdez (1989): Oil tanker accident; ~$1 billion in losses in law suits/fines
	Piper Alpha Disaster (1988): Occidental Petroleum's off-shore oil platform explosion; 167 killed; ~2 billion in losses
	Bhopal Gas Tragedy (1984): Methyl isocyanate leak at Union Carbide's pesticide plant; 5000-15,000 killed; ~120,000 injured; ~ 1 billion in losses; Worst ever industrial disaster
Electrical	*North East Power Blackout (2003):* Massive power outage that affected an estimated 10 million people in Ontario and 45 million people in eight U.S. ~$6 billion in losses
Mining	*Massey Energy (2010):* W. Virginia mine explosion; 29 killed; worst mine disaster in four decades; ~$130 million in losses
Pharmaceutical	*Schering Plough Inhalers Recall (2002):* 59 million inhalers for treating asthma were recalled; $500 million in fines; largest in FDA history
Financial	*Madoff Scandal(2008-09):* Outright fraud; Ponzi scheme; estimated $65 billion in losses; thousands of investors defrauded
	Subprime mortgage (2007-08): Caused by the end of the real estate bubble; precipitated a global financial crisis; trillions of dollars in losses; required governmental rescues in several countries
	Lehman Bros (2008-09): Collapse of a 158 year old tony Wall Street firm; one of the largest bankruptcies in the US, triggered by excessive risk taking and the collapse of the subprime mortgage market; ~26,000 employees lost their jobs
	WorldCom (2002): Accounting fraud; ~$180 billion in market value lost; 57,000 employees lost their jobs; billions of dollars lost in retirement savings
	Enron (2001): Outright fraud – overstatement of profits through off-the-books partnerships aided by its auditor Arthur Andersen; one of the largest bankruptcies in the US; ~$60 billion in market value destroyed; 20,000 employees lost their jobs; billions of dollars lost in retirement savings
	Savings and Loan (1980s): Caused by deregulation and real estate speculation; about 1000 S&L companies failed; ~$160 billion in losses, bailed out by theU.S. tax payers
Societal	*Collapse of Mayan Civilization (~800-900 AD):* several theories have been offered; most notable is environmental/ecological collapse
	Easter Island civilization (~ 1500 AD): several theories have been offered; most notable is environmental/ecological collapse

Systemic Failures: Different, Yet Same

- While these are different disasters that happened in
  - Different domains
  - Different facilities
  - Triggered by Different Events
  - Involve Different Chemicals, and so on
- There are, however, certain common underlying patterns behind such systemic failures
- People typically analyze only their domain and not cross-domains
- These patterns can teach us important fundamental lessons that we had better

Complex Systems: Fragility

- Need to go beyond analyzing them as independent one-off accidents
- Complexity: Large Network of Interacting, Interdependent, Systems and Sub-systems
  - Thousands of Components or more
  - Complex configurations
  - Nonlinear interactions leading to "Emergent" behavior
  - Behavior of the Whole is more than the sum of its Parts
- Modern plants are more difficult to design, control, diagnose and manage
  - Running processes near their limits due to RTO reduces margin for error
  - Plant-wide integration makes reasoning difficult
  - Fewer experienced operating personnel due to downsizing

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Failures (Lessons) at all levels

- Individual
- Corporation
- Corporate Board
- Government: Policies and Regulators
- Community
- National

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Failures (Lessons) at all levels

- Individual
  - Poor operator training and lack of experience
  - Not enough personnel due to downsizing
- Equipment
  - Poor wear-and-tear due to changing maintenance cycles
  - Wrong material, capacity, equipment due to new product mix
- Safety Systems
  - Safety systems not tested and maintained properly
  - Back-up and/or emergency systems on manual, not automatic

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Failures (Lessons) at all levels

- Procedures
  - Standard operating procedures not appropriate / followed, workers make up their own or perform short cuts
  - Past mini-accidents and warnings ignored
  - Process hazards analysis (PHA) not conducted thoroughly
  - Poor emergency planning and training

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Failures (Lessons) at all levels

- Management
  - Failures in communication between ranks
  - Safety is not made priority #1, cost cutting is
  - Senior management lacking the background to appreciate the risks inherent in system
  - Too much emphasis on financial spreadsheets and not enough on process flowsheets in complex process plants
  - "Performance at all costs" culture encouraging excessive risk taking and unethical behavior among its employees

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Failures (Lessons) at all levels

- Corporate Board
  - Rewarding short-term performance rather than long-term
  - Setting up perverse incentives detrimental to long-term success of company
- Government: Policies and Regulators
  - Laissez-faire government policies, reliance on self-policing
  - Policies not strictly enforced due to limited resources or inherent conflicts of interest (as seen in SEC and MMS)

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Failures (Lessons) at all levels

- National
  - Anti-government or anti-regulation sentiment dominant
  - Sustainability warnings ignored
  - Celebration of greed

- What is THE CAUSE?
- What factors and patterns increase risk?

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Individuals	▪ Poor operator training or inexperienced operators leading to human errors ▪ Not enough personnel due to downsizing
Equipment	▪ Poor maintenance and wear-and-tear leading to equipment failure ▪ Wrong material, capacity, or equipment
Procedures	▪ Standard operating procedures not followed, workers make up their own or perform short cuts ▪ Past mini-accidents and warnings ignored ▪ Process hazards analysis (PHA) not conducted thoroughly ▪ Poor emergency planning and training
Safety Systems	▪ Safety systems not tested and maintained properly ▪ Back-up and/or emergency systems not on automatic but on manual
Management	▪ Failure in communication between ranks ▪ Safety is not made priority #1, cost cutting is ▪ Senior management lacking the background to appreciate the risks inherent in complex process plants – too much emphasis on financial spreadsheets and not enough on process flowsheets ▪ "Performance at all costs" culture encouraging excessive risk taking and unethical behavior among its employees
Corporate Board	▪ Rewarding short term performance instead of long term ▪ Setting up perverse incentives that are detrimental to the long term survival of the company
Government: Policies and Regulators	▪ Laissez-faire regulatory policies, reliance on self policing ▪ Policies not strictly enforced due to limited resources or inherent conflict of interests of the regulatory bodies (as seen in SEC and MMS)
National: Political	▪ Anti-government or anti-regulations sentiment dominant ▪ Sustainability warnings ignored ▪ Celebration of greed

Systemic Failures: Common Patterns

- Major disasters rarely occur due to a single failure of an equipment or personnel.
- Even though the senior management typically tries to spin the blame as some unanticipated equipment failure, an operator error, or a rogue trader, that is rarely the case for major disasters.
  - Bhopal (Union Carbide)Disgruntled employee sabotage
  - Piper Alpha (Occidental) Pump failure
  - Enron Andy Fastow did it!
- Again and again, investigations have shown that there are always several layers of failures of equipment, systems, processes and people that led to major disasters.

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Systemic Failures: Common Patterns

- Studies have shown that the safety procedures had been deteriorating at the failed facilities for weeks, if not for months or years, prior to the accident
  - OSHA statistics show BP ran up 760 "egregious, willful" safety violations: Sunoco (8), Conoco-Phillips (8), Citgo (2), Exxon (1)
  - Bhopal: No testing of safety back-up systems for months
  - Piper Alpha: Permit to Work system broken down, emergency pumps not in auto mode, ...
  - Madoff Ponzi: Markopolos complained to the SEC for several years, ...
  - Enron: Management and auditors cooking the

Systemic Failures: Common Patterns

- People had not identified all the serious potential hazards
- Failed to conduct a worst case analysis (PHA)
  - BP, Piper Alpha, Bhopal
  - Financial: What if house prices did not rise year over year?
  - But some did! See Michael Lewis: "The Big Short"
- Inadequate training of the plant personnel to handle serious emergencies
- Top management had only paid a lip service to safety
- Resulted in a poor corporate culture

Regulatory Environment Failure

- Self policing does not work
  - Does not matter: Chemical, Petrochemical, Pharmaceutical, or Financial
- This seems so obvious that people should not have to die, or lose all their money, to make us realize this
- Need independent agencies without inherent conflicts
- Rating agencies were dependent on their Wall Street clients for their business and, therefore, merrily went stamping AAA ratings on junk
- Minerals Management Service was inherently conflicted between its goals of awarding leases to collect revenues and

Systemic Risk: Lessons

- Personnel Issues
- Regulatory Issues
- Corporation/Management Issues
- Technology Issues
- Fundamental Conceptual/Intellectual Issues

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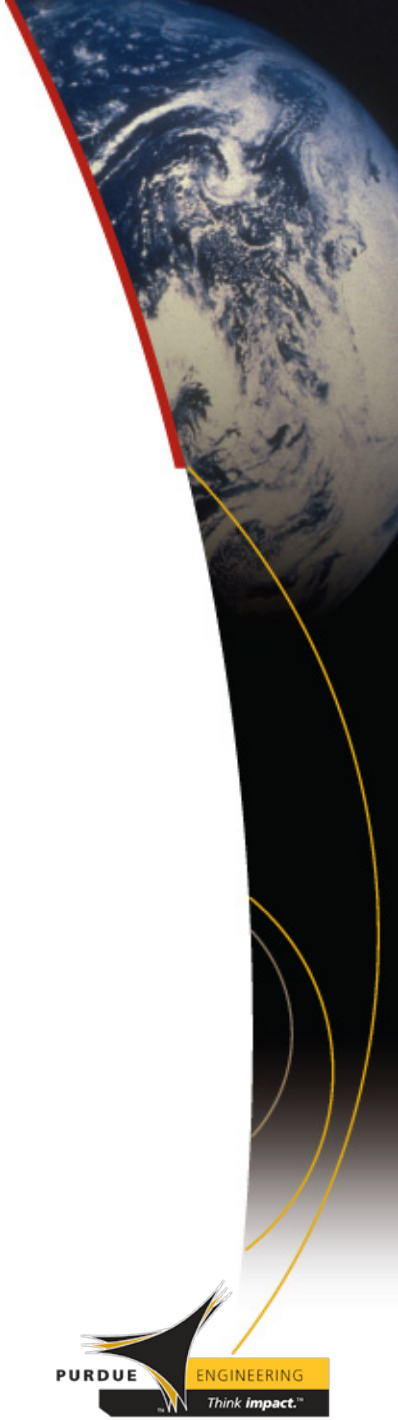
Systemic Risk

Fundamental Conceptual/Intellectual Challenges



Systemic Risk: Lessons

- Need intelligent real-time operator support
  - Prognostic: Anticipate Problems
  - Diagnostic: Effectively and Safely Manage Problems
- Instead of the React-and-Fix approach, we need to anticipate and manage "emergent" behavior better
- Thorough Process Hazards Analysis: Worst-case
- Advanced Simulators for Operator Training

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Decision Support Needs of Operators

- Inadequate anticipation of process disturbances
- Lack of real-time, root-cause analysis
- Lack of distinctions between instrument failures and true process deviations
- Poor integration of multiple information and control system components.
- Lack of adequate tools to access past records of abnormal situations.

Need Intelligent Control

Intellectual Challenges

- Complexity Science
  - How do you predict "emergent" behavior?
  - How do you systematically identify all potential hazards in a complex system?
- Multi-scale modeling
  - Going from Parts to Whole
  - Functional, Behavioral, and Causal Models of Complex Engineered Systems
- Hybrid Intelligent systems for Decision-Making
  - Design, Control, Diagnosis, Optimization

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AEM & PHA

Prognosis (Design)

P H A

- *Causes*
- *Basic Events*

- *Symptoms*
- *Consequences*
- *Faults*

A E M

Diagnosis (Control)

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PHA Approaches

- HAZOP
- Fault Tree Analysis (FTA)
- What If Analysis
- Check Lists
- Failure Effects and Mode Analysis (FMEA)

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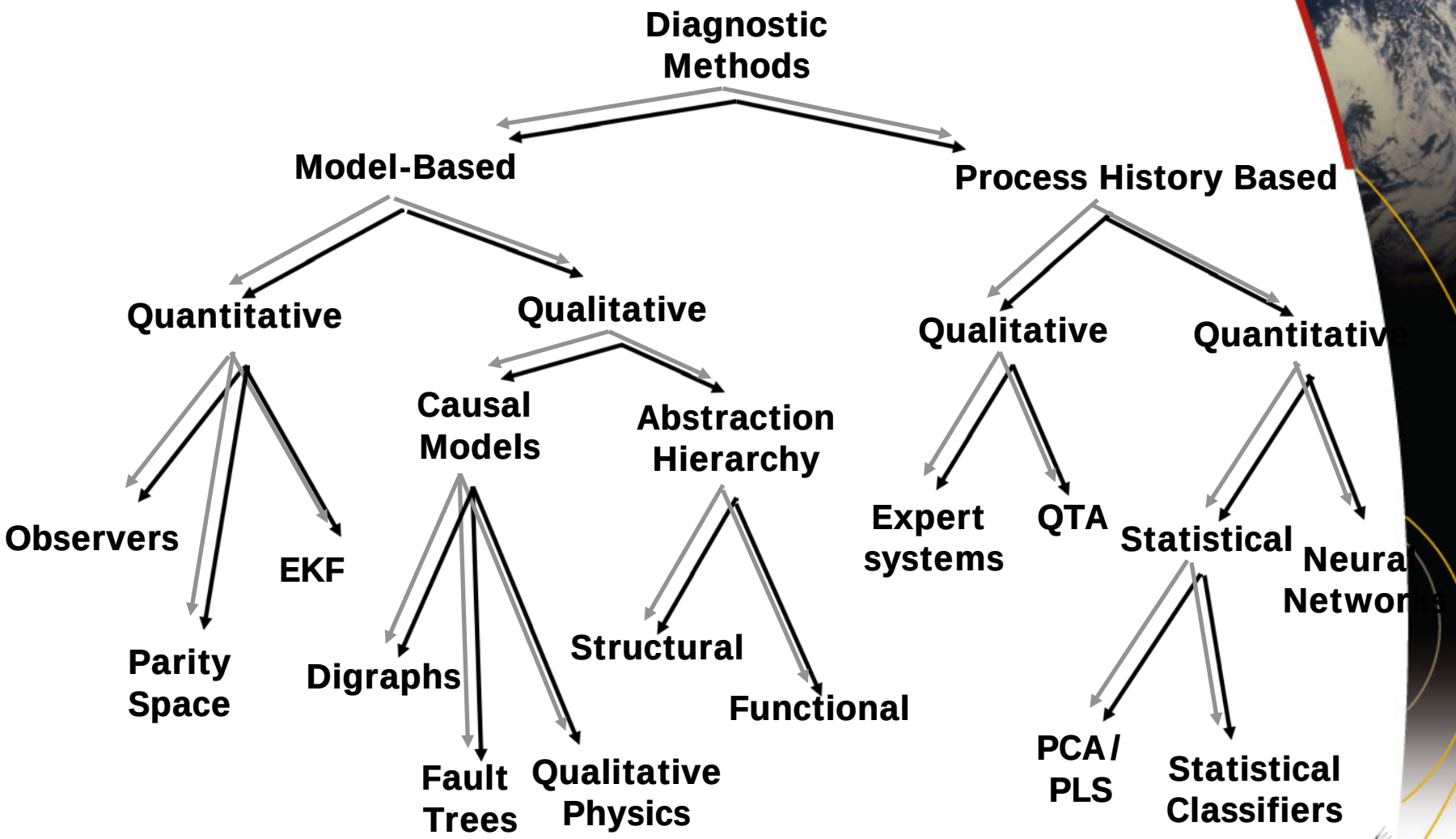
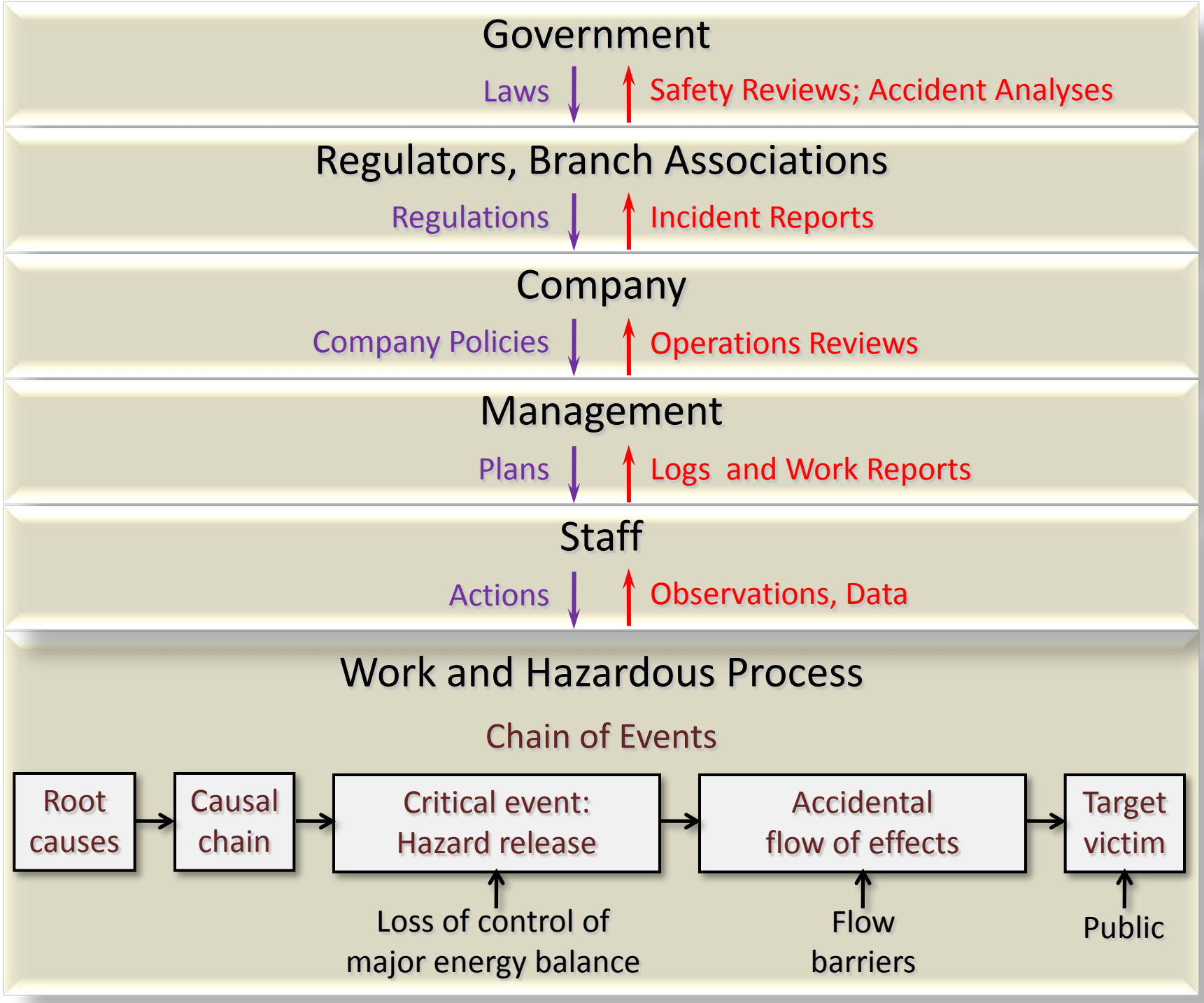
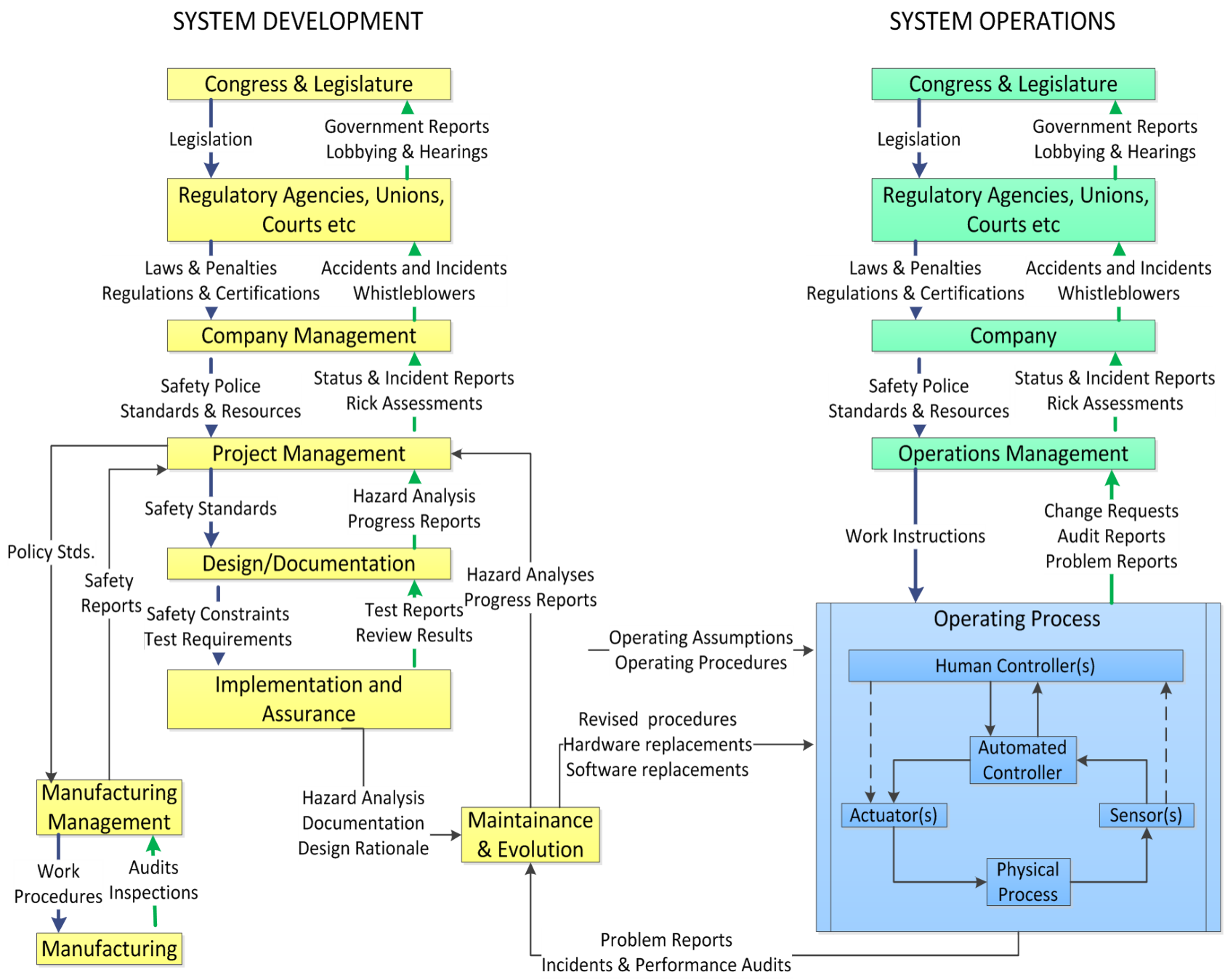
Approaches to Intelligent Control



V. Venkatasubramanian, R. Rengaswamy, K. Yin and S. N. Kavuri, "Review of Process Fault Diagnosis - Part I, II and III", Computers and Chemical Engineering, 27(3), 293-346, 2003


Government
Laws
Safety Reviews; Accident Analyses
Regulators, Branch Associations
Regulations
Incident Reports
Company
Company Policies
Operations Reviews
Management
Plans
Logs and Work Reports
Staff
Actions
Observations, Data
Work and Hazardous Process
Chain of Events
Root causes
Causal chain
Critical event: Hazard release
Accidental flow of effects
Target victim
Loss of control of major energy balance
Flow barriers
Public


SYSTEM DEVELOPMENT
Congress & Legislature
Legislation
Government Reports
Lobbying & Hearings
Regulatory Agencies, Unions, Courts etc
Laws & Penalties
Regulations & Certifications
Accidents and Incidents
Whistleblowers
Company Management
Safety Police
Standards & Resources
Status & Incident Reports
Rick Assessments
Project Management
Safety Standards
Hazard Analysis
Progress Reports
Policy Stds.
Safety
Reports
Design/Documentation
Hazard Analyses
Progress Reports
Safety Constraints
Test Requirements
Test Reports
Review Results
Implementation and Assurance
Manufacturing Management
Hazard Analysis
Documentation
Design Rationale
Maintainance & Evolution
Work
Procedures
Audits
Inspections
Manufacturing
SYSTEM OPERATIONS
Congress & Legislature
Legislation
Government Reports
Lobbying & Hearings
Regulatory Agencies, Unions, Courts etc
Laws & Penalties
Regulations & Certifications
Accidents and Incidents
Whistleblowers
Company
Safety Police
Standards & Resources
Status & Incident Reports
Rick Assessments
Operations Management
Work Instructions
Change Requests
Audit Reports
Problem Reports
Operating Process
Operating Assumptions
Operating Procedures
Human Controller(s)
Revised procedures
Hardware replacements
Software replacements
Automated Controller
Actuator(s)
Sensor(s)
Physical Process
Problem Reports
Incidents & Performance Audits

Return to Barrett

Dekker Perspectives on Robustness and Recovery

- Actors Cannot Have Perfect Knowledge of Complexity
- Local Effects, Local Motivations Dominate Decisions Based on Understandings at the Time
- Drift into Failure/ Drift into Success
  - Series of small actions with ripples
  - What is considered normal behavior?
  - Responses to prior experience

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Emerging Systems as Patterns and Stories

- Human Information Processing as Fundamental Pattern Making / Matching
  - Making "enough" sense, not always "correct"
  - Heuristics, illusions, superstitions, tests
- Root Cause Analysis Has Benefit of Hindsight
  - We tell stories here, too
  - "Arrow of time / progress"
- What was Understanding ***At That Time***?
  - Stories fueled by "gray and grain"

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Experience: Associating Patterns of Events

- Importance of Examining Patterns of Causes
  - Events clustered in time or task phase give cues
  - Disparate events with similar groupings of causes
  - Avoiding bias of rare events
- Managing Tasks and Resources
  - What are personnel constraints, coordination processes, options for robust performance?
  - What are recovery processes, not just error processes?

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Changing Approaches to Incident and Event Analysis

- Error and Recovery Studies Across Domains
  - Rasmussen, Reason, other approaches
- Medical Adverse Event Environment
  - Moving from "bad actor" to "degraded system"
- NASA Investigations of *Challenger* and *Columbia* Accidents
- Robustness is Not More Aggressive Search for "The Bad Component"

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Proximal vs. Distal Root Causes, THERAC and *Challenger*

- Proximal Causes:
  - "Human Error" on operator (poor decision)
  - Machine malfunction (hardware failure)
  - Software / system error (not programmer error?)
- Distal Causes:
  - Organisational blindness (hiding / misrepresenting events)
  - Poor human performance considerations (impact of social factors)
  - Wrong level of root cause analysis

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Systematic Distal Causes of Problems and Events

- Sidney Dekker, *Drift into Failure*
- Normalisation of Deviance Perspective
  - "We've been able to do it this way before"
  - "It seems to work this way"
  - "Naysayers are just paranoid"
- Poor Understanding of System Dynamics
  - Limited analysis of control ranges and variances in sub-critical events or near-misses
  - Unclear impact of hysteresis, lags, unclear coupling of system components
  - Reason Swiss Cheese analysis, quantitative style

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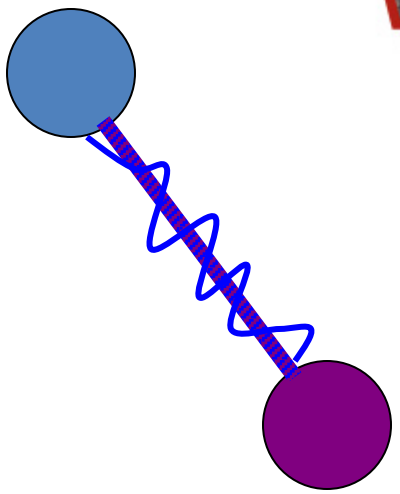
Information Alignment as Coupling

- Effective Transfer from Entity to Entity
  - Flows without loss or entries of noise
  - Understanding of causes through effects
- Organisational Coupling as Reason Focus for Root Cause Analysis (RCA)
  - Quality Analysis / Quality Investigation Linkages
    - Discovery approach to collect data
    - Investigation approach to determine causes
    - Organisation improvement to respond



Performance Shaping Factors: Examples from Different Types

- Individual
  - Domain Skill, Expertise, Sensory Acuity, Physical Training
- Environmental
  - Noise, Lighting, Vibration, Temperature, Toxins
- Technological
  - Machinery Design, Interface Complexity (Ergonomics), Information System Implementation (Info Alignment)
- Organisational
  - Normalisation of Deviance, Hierarchies, Culture of Blame, Conflicting Policies and Incentives

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Determining Root Causes from Adverse Events

- Errors, Precursors, Captures
  - Where are "human errors" attributed?
    - Operators vs. managers vs. designers
  - Conceptual models of system performance and use
    - Evolution of "rational man" to "reasonable person"
  - What conditions make errors more likely?
    - Evolving sense of "performance shaping factors"
  - Is an error caught still an error?
    - Still an open question

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Conceptualizations of System Performance: Dynamics Language

- Stability
  - Whether disturbance with feedback returns to ongoing intended function
- Robustness
  - System ability to withstand disturbance of given magnitude and continue intended function
  - "armored against"
- Resilience
  - System ability to return to intended function after disturbance of given magnitude
  - "recovery from"

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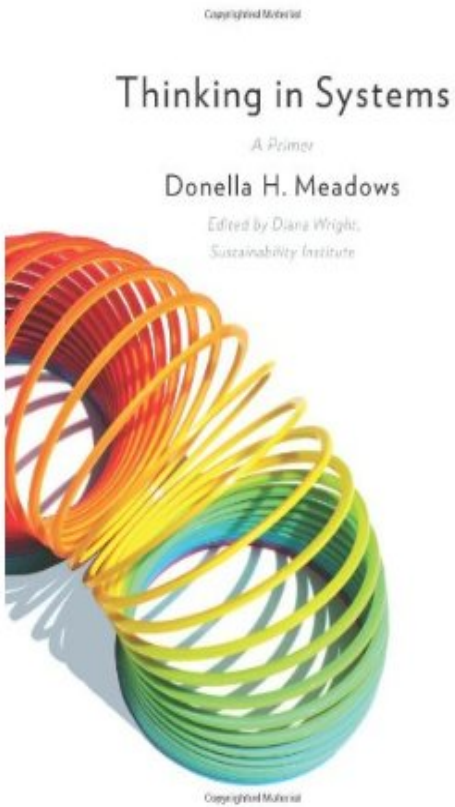
Why Are Systems Dynamics Discussions Difficult?

- Newton vs Weiner
  - Clockwork (1680) vs Cybernetic (1950) philosophies
- Differential Equation Models?
- Lags, Gains, Effect Orders?
- Forms of Presentation?
  - Donella Meadows, *Thinking in Systems*



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Discussion

- Additional Debates, Directions, Disagreements
- Where is the Argument?
  - How it should be?
  - How we want it to be?
  - How it is for people like us?
  - How it is for lesser beings?
- Cynicism, Optimism, Pessimism, Realism

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Conclusion

- Single Root Cause Model as Artifact of Philosophy, Culture
- Large Scale Accidents Bely This Model
- Creating and Reconstructing System Dynamics, Risks, Stories, Understandings
- "Drift Into Failure" as Factors and Perspectives Influencing System Risk
- Where are Lessons that Will Help Us?
- Thinking via Systems Dynamics
  - "Thinking in Systems?"

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