CHARCTERIZATION AND MODELING OF COMPLEX ENGINEERING SYSTEMS

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Adopt the universal Darwinism argument that systems become complex through variation and selection along with the ability to self-organize leading to an ever-increasing complexity by adding and/or re-organizing structures and functions, and more relations within and between functions and structures of the system, all to attain some fixed and emergent objectives and goals.

- Epistemology and systems description

- Backgrounds and system description theories

- A theory of complex systems

- Properties of complexity and complex systems

- A functional-structural model of complex systems

- A representation framework

- Examples

- Conclusions

- Complex system description requires explanation of knowledge

- Start with "What there is to know about knowing itself?"

- Knowledge description vs. Knowledge representation

- Evolutionary epistemology sees knowledge itself as a product of the variation and selection processes characterizing evolution and notes that the prime function of knowledge is to make survival and reproduction possible.

- Aristotle developed a hierarchical representation of knowledge about objects and their components in the world –the *whole* has attributes more than sum of its *parts*.

- Christianity argued knowledge is unnecessary, everything to know is in Holy Scriptures, the material world inconsequential compared with heavenly matters.

- Eastern philosophies offered spiritual meditation and stoic acceptance of the world.

- Islamic philosophers renewed epistemology through scientific inquiries, but retaining the Greek's *monoism* views of knowledge as a blend of material and supernatural.

- Renaissance: Francis Bacon "knowledge begins with experience and proceed by induction to principles (empiricism)"; René Descartes "new knowledge can be found without having to experience things through rationalism and deductive analyses such as the *reductionism*, and also formed *dualism*" ; Immanuel Kant combined rationalism and empiricism, noted that rationalist ideas are simply empirical conditions of the mind (idealism)

- Dualism opened scientific inquiries such as Newton's and later Charles Darwin's theory of evolution.

- Computers amplified interest in epistemology by bringing ancient philosophical debates to experimental analysis, modeling and effective use as in artificial intelligence, theory of mind, formation of knowledge: Reductionism vs. holism; Functionalism vs. structuralism; Computation vs. connection

- **Evolutionary epistemology**: systems with better knowledge of their internal and external environments have far superior chance of survival and flourishing.

- **H. Simon** tied natural evolution to formation of organizational hierarchy in complex engineered systems.

- **E. O. Wilson** advocates much of what is known and will be known is tied together and discusses a biological system complexity metaphor.

- **Gell-Mann and Holand** have established the "Santa Fe school of complexity" in which they claim that adaptable systems become complex with properties as aggregate, nonlinear, flows, and diversity.

- **Kauffman** reiterates the Santa Fe school and claims that Darwin's theory is not enough to describe where we are today, and describes the concept of "the edge of chaos"

- Heylighen defines complexity as the combination of *distinction* or *differentiation* (variety), and *connection or integration* (dependency) in *spatial*, *temporal* and *scale* dimensions. The connections make interdisciplinary linkages in the system leading to organizations that are composed of human, mind, society, and technology

- The *law of requisite variety*, which asserts that a larger inventory of possible *actions* possessed by a system allows it to survive (fulfill the needs) in a larger variety of situations (environment), and consequently becomes fitter.
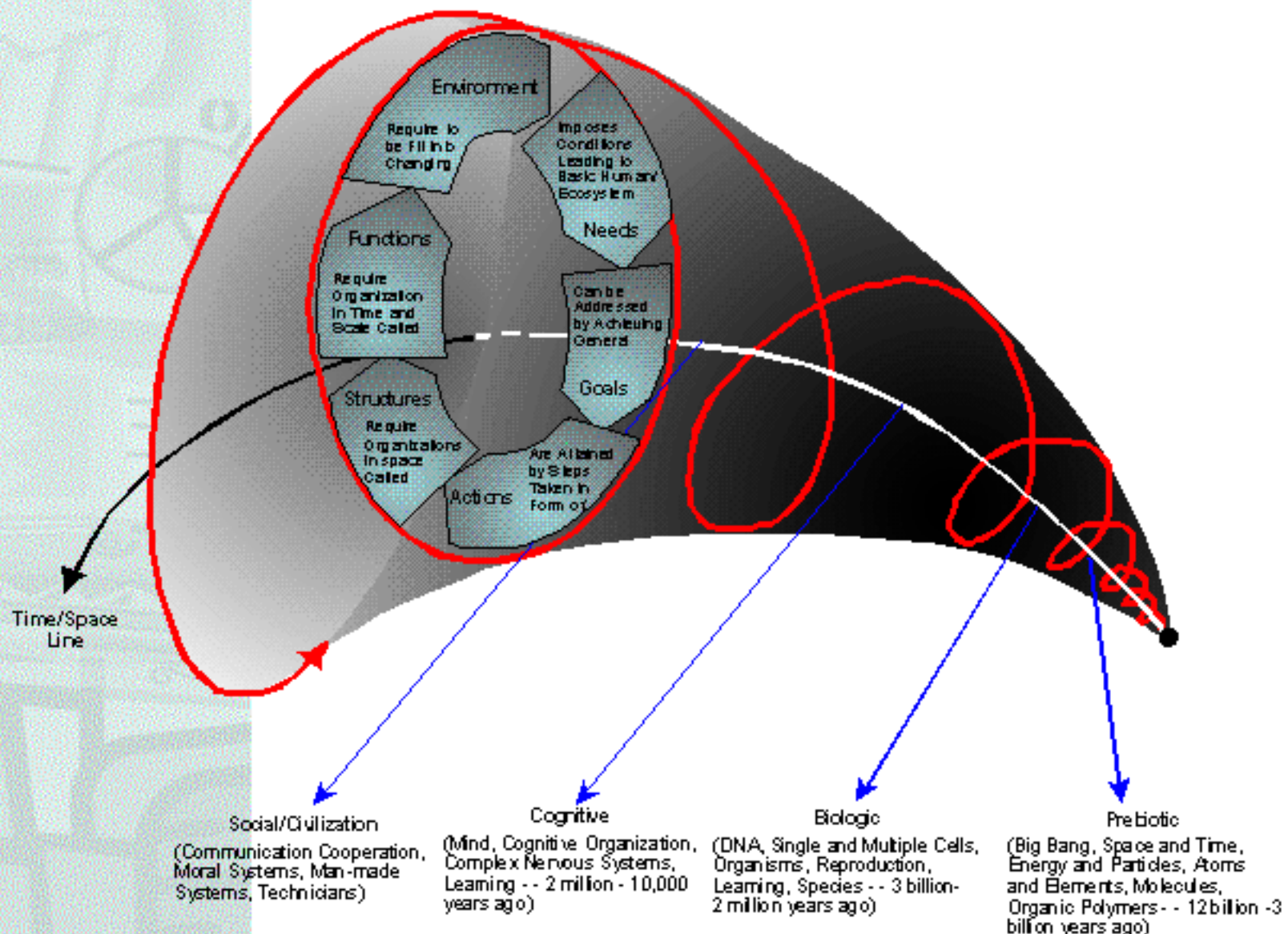
- As the number of the actions needed increases, so does coordination and stability of system activities (control functions) leading to an organization of integrated and cooperating groups of related activities (functions), and thus a functional hierarchy.

- Functions are realized by structures.

- More complex structures require and deliver more complex set of functions and vice versa.

- Intelligence is also a result of systems increased complexity.

- Albus and Meystell define engineering *intelligence* as the ability of the system to behave appropriately in uncertain environments.

- Now A Theory: Intelligence is result of increased complexity. Engineered systems emerge and evolve to cope environments such as internal and external physics of the systems, competitive pressures in the marketplace, that impose needs which the system must act to fulfill. Those systems that are successful attain a set of goals (consistent and set by the needs), and their organizations will survive and multiply. Those that lose will be abandoned.

- Maslow's theory of needs: *Physiological, Safety, Love and Belonging, Esteem, and Self-actualization* .

Environment

Require to be Fill in b Changing

Imposes Conditions Leading to Basic Human Ecosystem

Needs

Functions

Require Organization In Time and Scale Called

Can be Addressed by Achieving General

Goals

Structures

Require Organizations in space Called

Are Attained by Steps Taken in Form of

Actions

Time/Space Line

Social/Civilization

(Communication Cooperation, Moral Systems, Man-made Systems, Technicians)

Cognitive

(Mind, Cognitive Organization, Complex Nervous Systems, Learning - - 2 million - 10,000 years ago)

Biologic

(DNA, Single and Multiple Cells, Organisms, Reproduction, Learning, Species - - 3 billion - 2 million years ago)

Prebiotic

(Big Bang, Space and Time, Energy and Particles, Atoms and Elements, Molecules, Organic Polymers - - 12 billion - 3 billion years ago)

- Due to Campbell, the whole to some degree constrained by the parts (upward causation)—as in reductionism, but parts to some degree constrained by the whole (downward causation). Any modeling should consider this fact, beyond the representation of the system's organization in form of function and structure hierarchy.

- Modeling complex systems requires *learning* and *knowledge*. Knowledge is useful information about organization of structures and functions, environments, events, states, situations, relationships, cause and effects, tasks, goals, motives, values, plans, behaviors, perceptions, opinions, biases, experiences, rules of thumb, laws, etc. Learning can improve the chance of system success through improved knowledge.

- A system is fit if:

  1) its parts function individually and in harmony to attain implicit or explicit goals (i.e., the system is intrinsically a stable whole and "fits together"),

  2) the whole fits its environment, i.e. it can resist internal and external perturbations and profit from external resources to adapt and remain vital.

- **Evolving:** Complex systems tend to evolve in order to adapt, sustain and grow, primarily in an opportunistic, but goal-directed manner, leading to hierarchical organizations of structures with function and purpose. This also means that they retain memories of the past (i.e., they are history-bound to the previous states and often irreversible). Further, due to their multiple internal and external feedbacks evolving systems produce new environmental constraints and requirements.

- **Integrated:** Complex engineering systems have tightly and diversely coupled components (hardware, software, human, policy coupled with feedback loops) interacting in parallel and cooperatively. Interactions may be *uncertain* (random, unknown, or incomplete); *ambiguous* (linguistically not meaningful); *nonlinear* (effect is not proportional to the cause; and *counterintuitive* (cause and effect could be distant in time and space, while we usually look for events near the cause as in most root-cause analysis efforts); and *partially irreducible* (a system has properties more than the sum of its parts).
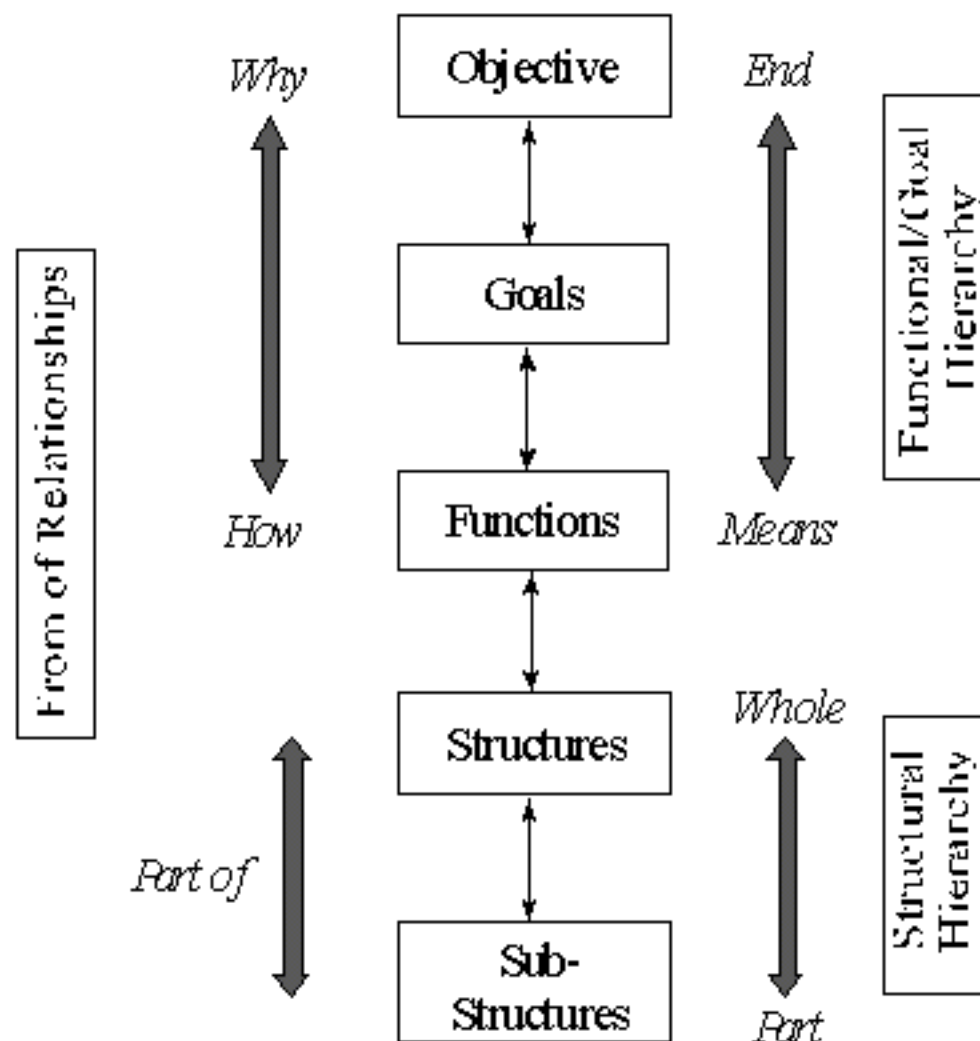
- **Dynamic:** Changes in the system may occur at many interacting time scales and primarily arises from feedbacks.

- **Large:** Subsystems of complex systems participate in multiple diverse processes and geographically wide structures (large-scale) and diverse functions utilized over long time (time-scale), and requiring multiple complementary levels of analysis (temporal-scale).

- **Intelligent:** They behave appropriately in uncertain environments by *self-organizing* (random and intended perturbations lead to known patterns in space and time that the system appropriately acts) and *learning* abilities (learns new ways to achieve its goals in the face of inter- and intra-system obstructions).
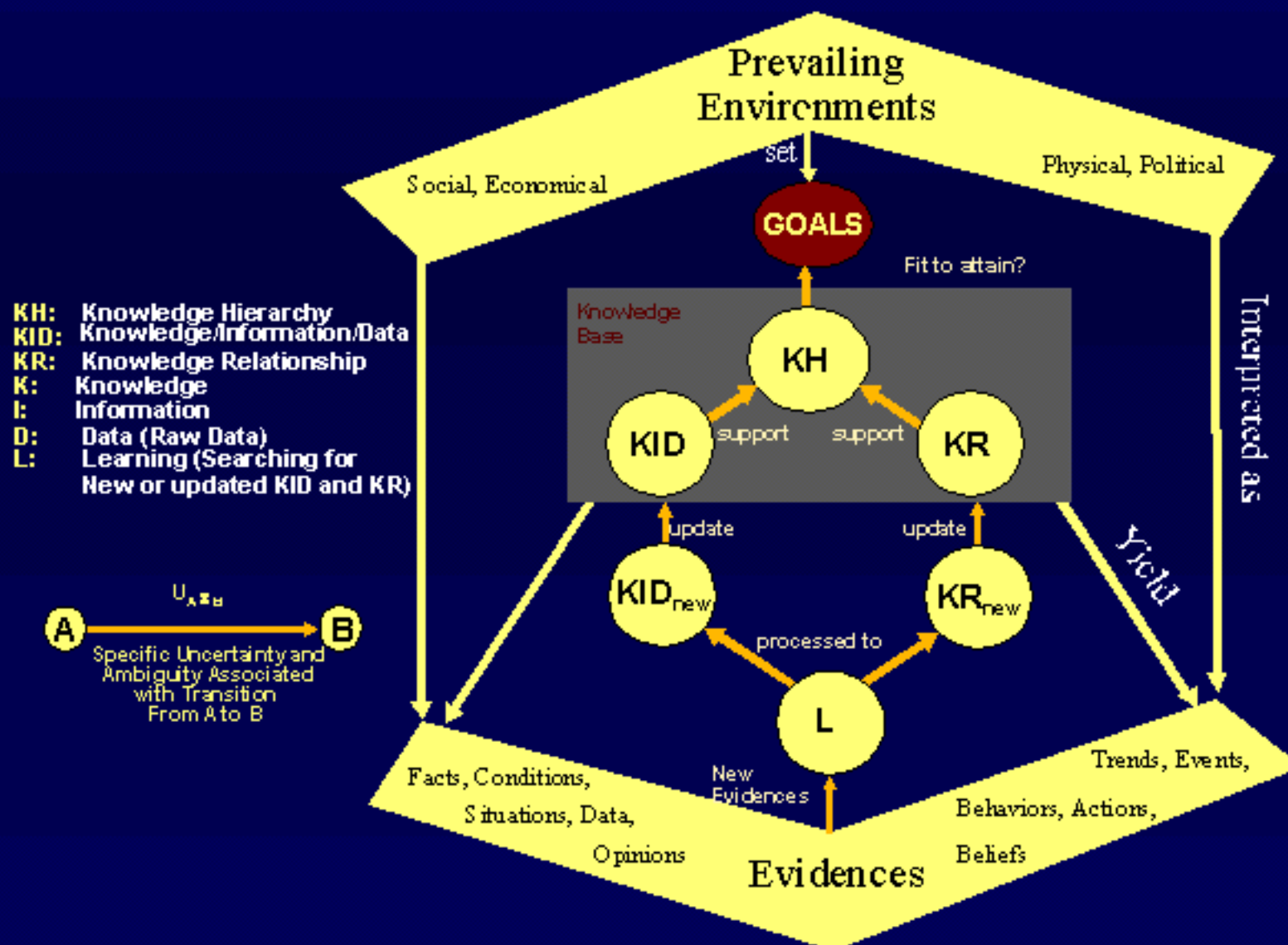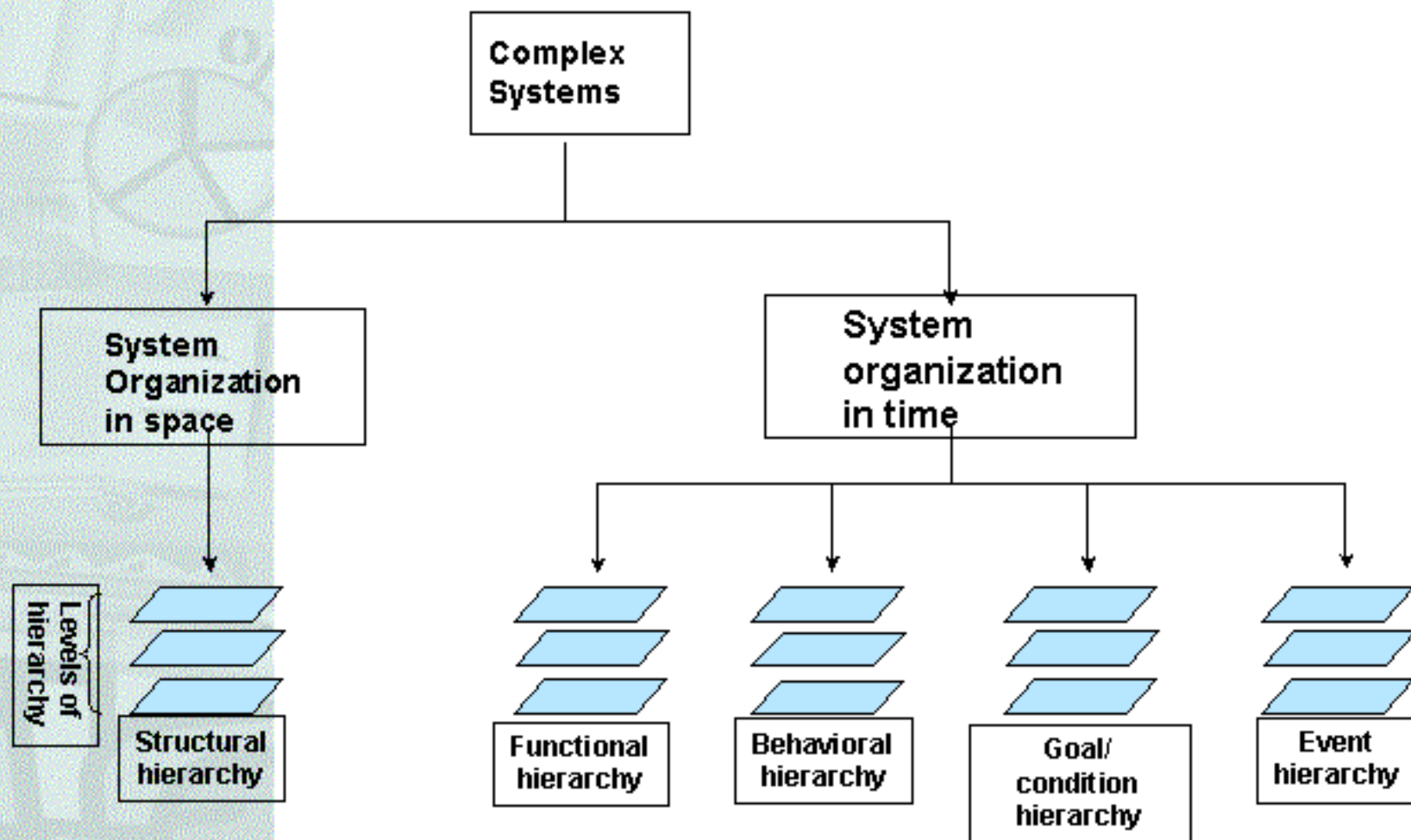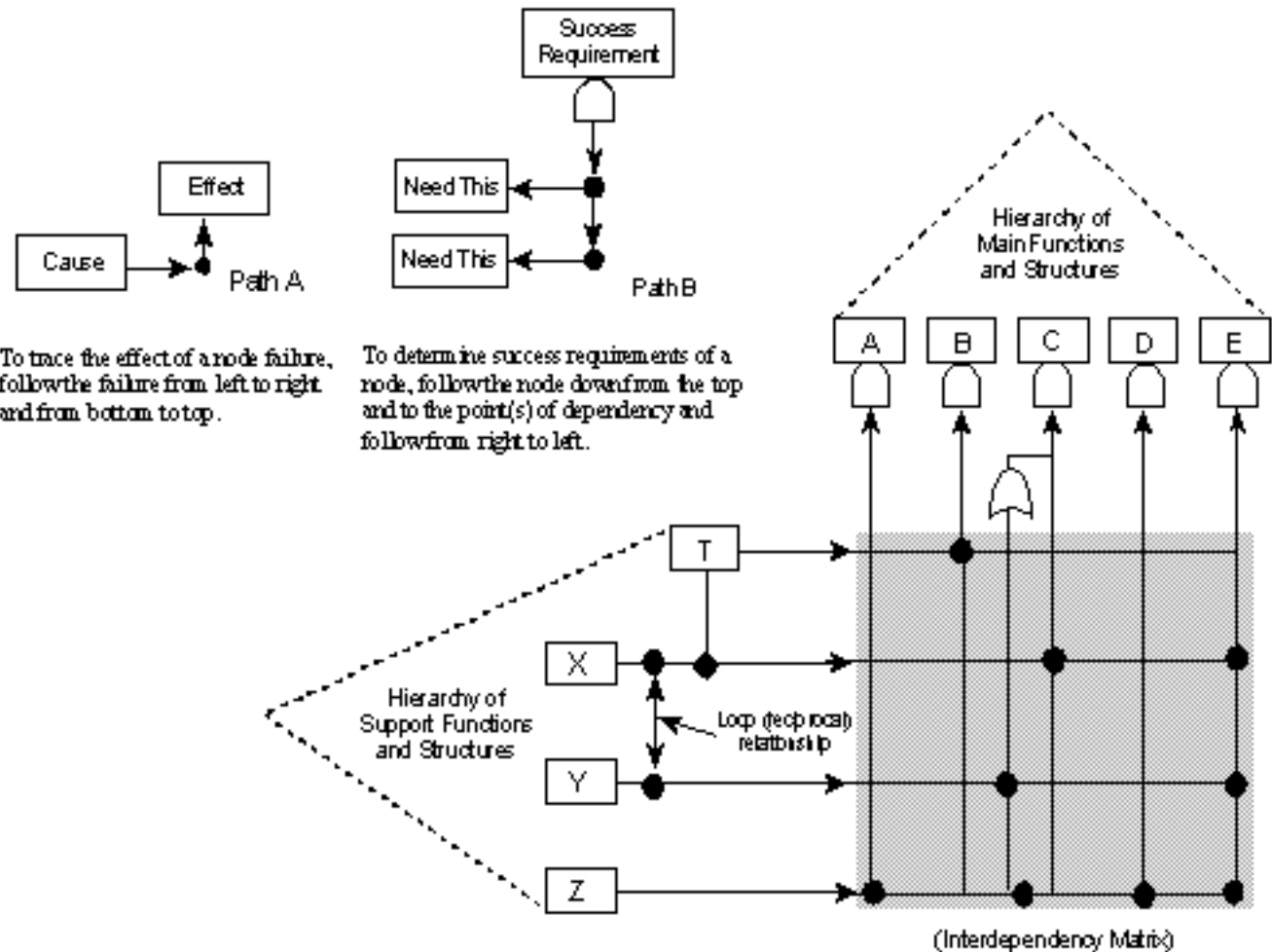
- Goals are ends toward which efforts are directed (viz. means) and are very general, and speak to the basic human/ecosystem needs that are to be addressed.

- System fitness may be measured as ability to achieve the system goals. Intelligent systems have an ultimate or highest-level goal, decomposable into sub-goals. Systems then generate actions designed to achieve those sub-goals and ultimate goal is eventually achieved.

- Engineering systems (and even organisms or human) pursue preconceived goals, resisting obstructions from the environment that may make it deviate from its preferred state of affairs. This, goal-directedness implies that systems also have self-organization abilities (e.g., functions) as feedback regulation and control over internal and external perturbations created or induced by their environment.

- Organization of systems can be defined by their structure with function.

- The complexity produced by differentiation and integration in the spatial dimension may be called "structural", in the temporal dimension "functional", in the spatial scale dimension "structural hierarchy".

- The level of detail (abstraction) in these hierarchies is relative.

- A *structure* can be viewed as the *organization of the system in space*.

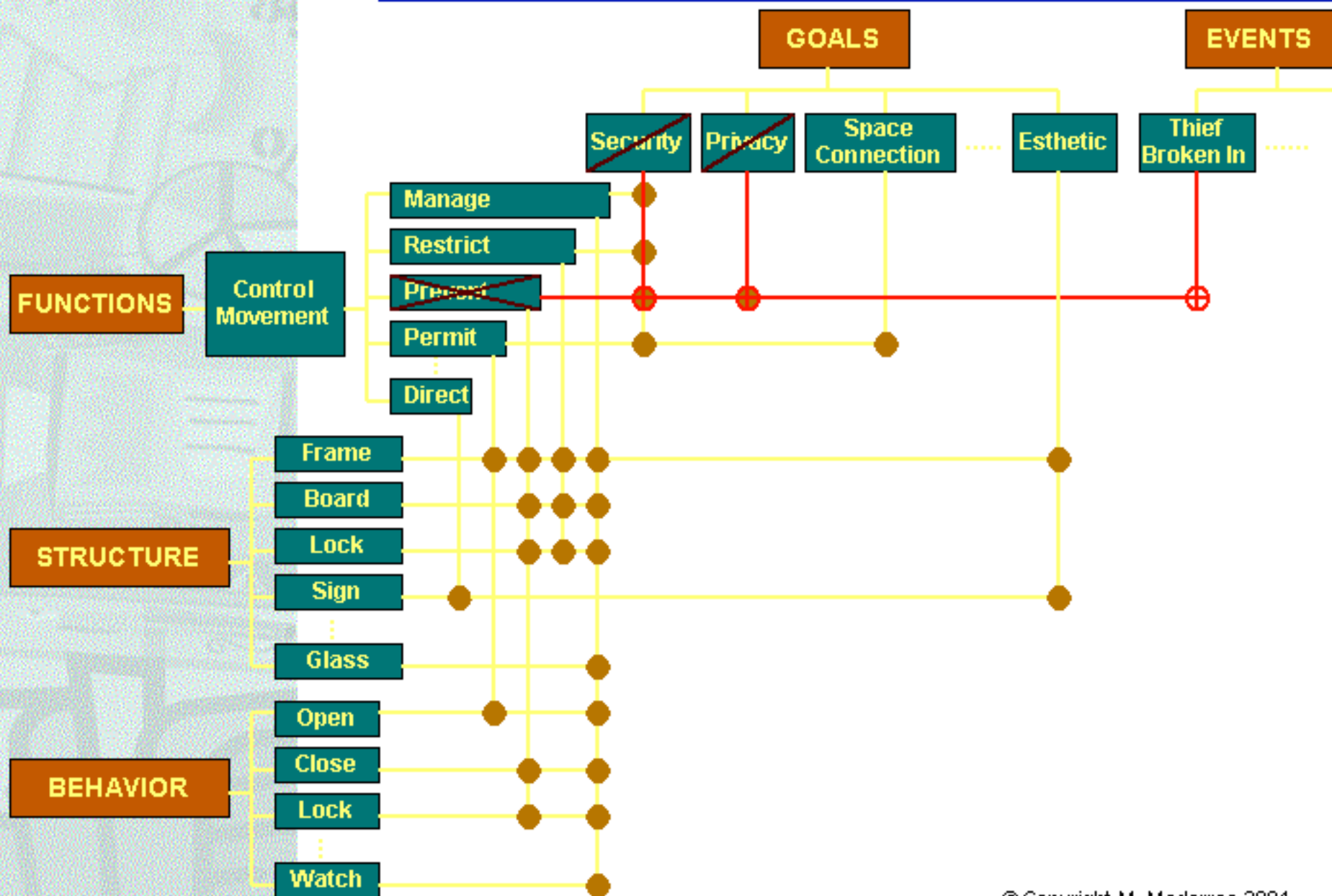- A *function* can be viewed as the *organization of the system in time*.

To trace the effect of a node failure, follow the failure from left to right and from bottom to top.

To determine success requirements of a node, follow the node down from the top and to the point(s) of dependency and follow from right to left.

(Interdependency Matrix)

Example for Modeling a Door

- shows the relationship between the main and support functions.

- **Main functions**:

  - attain system's objective and goals.

- ***Support* Functions**:

  - are auxiliary to main functions and help or facilitate a realization of the main functions.
  - In engineering support functions
    - provide a motive (e.g., power to run a component),
    - provide control and instrumentation, and
    - provide appropriate operating environment. (e.g., cooling, lubrication, and air conditioning).

- **_Six functional primitives_: describe the overall spectrum of intended and unintended behaviors**

1) *generate* : a commodity that did not exist is brought to existence
2) *destroy* : a commodity that existed is removed
3) *maintain* : a commodity that existed will continue to exist
4) *control* : a commodity will keep its forms but change its properties
5) *Transform* : a commodity changes its form to preserve predefined constraints
6) *transport* : a commodity moves from one location to another

A Syntax To Describe Functions Of Physical Systems
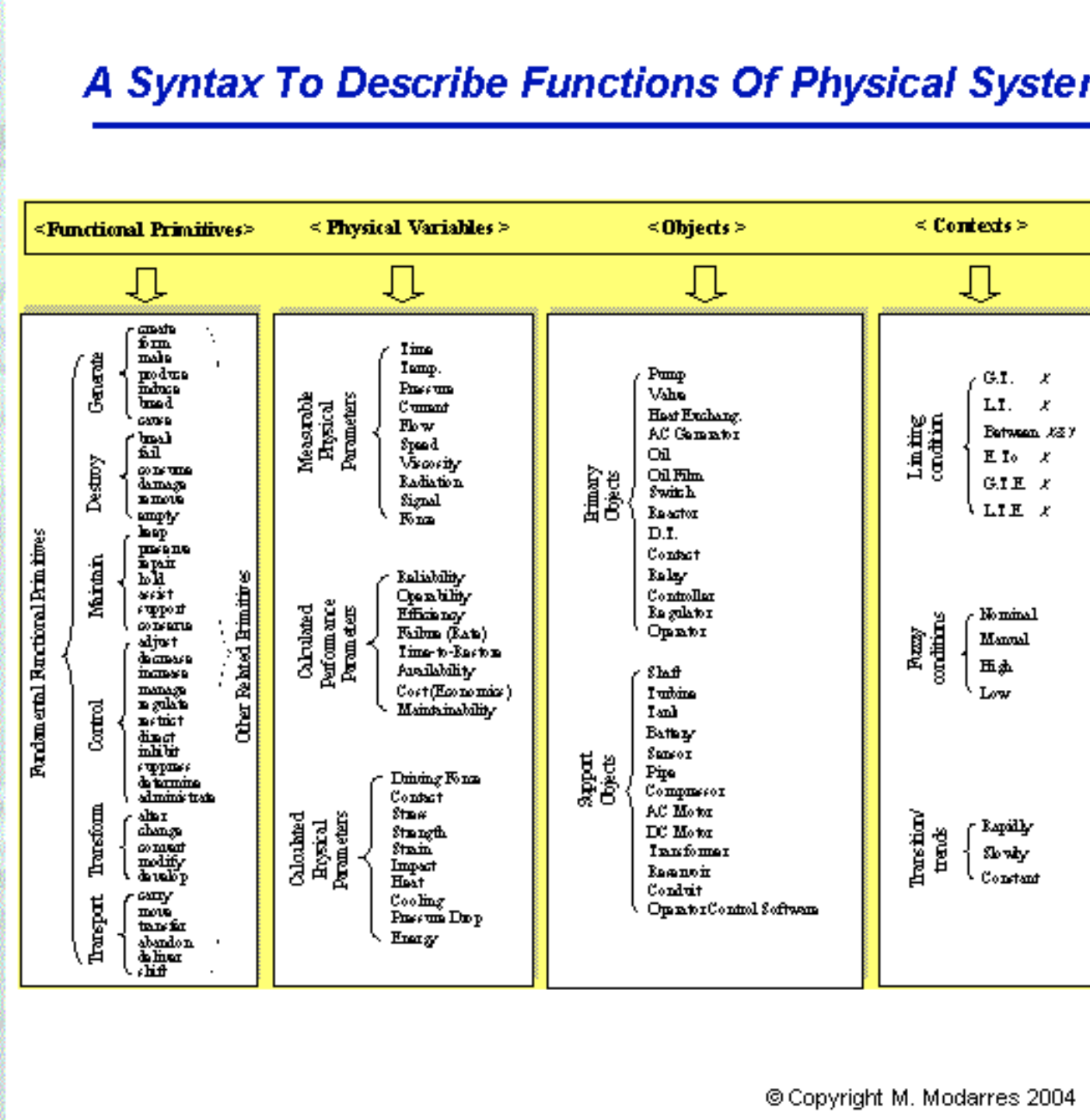
Water Hammer Phenomenon

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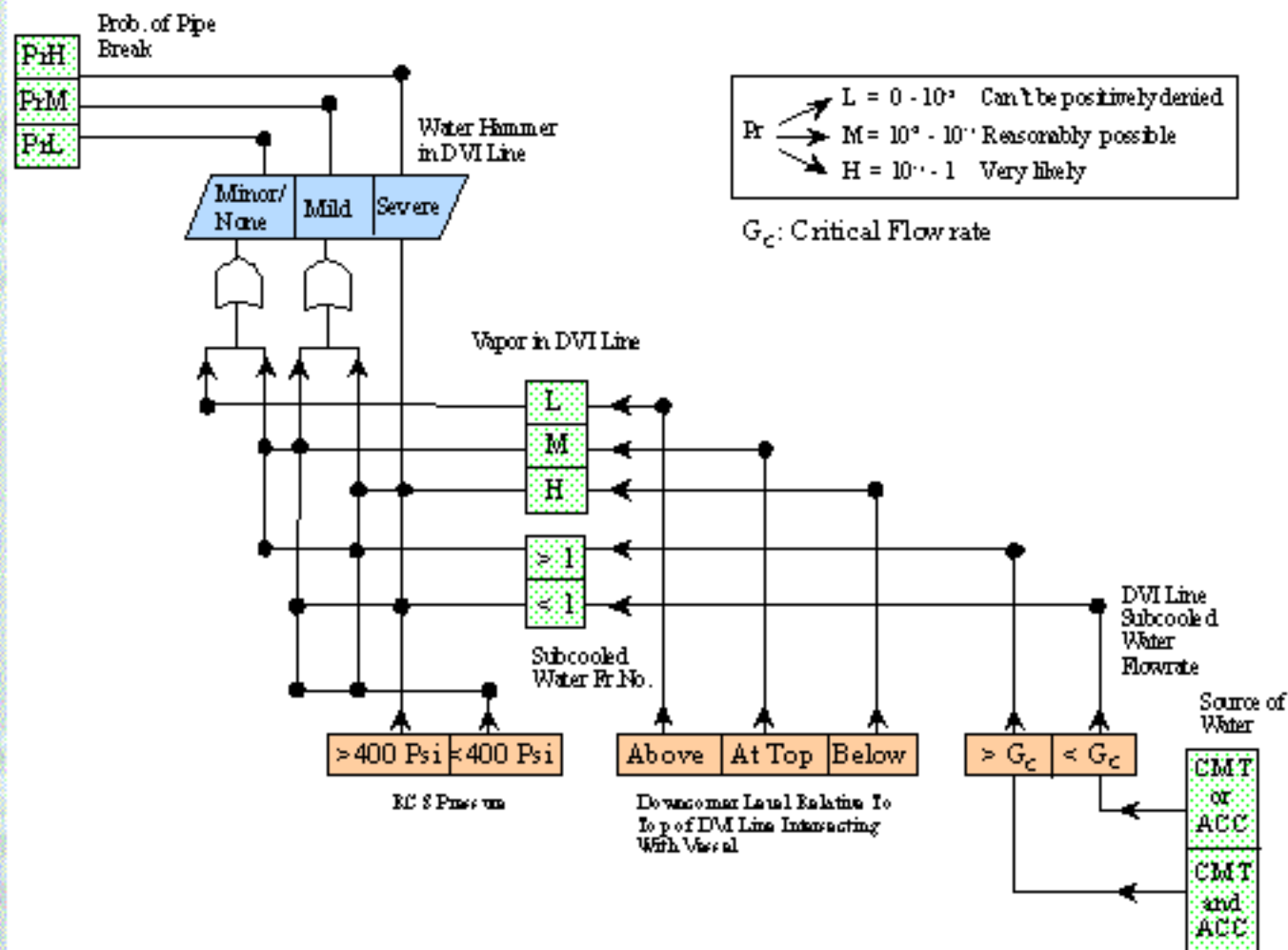
- Consider a company yearning to run as a customer-centric organization. As such functional, structural, goal and other knowledge hierarchies needed to attain this should be developed (deductively) and continuously evolved according to changes in the prevailing internal and external economic, and business environments.

- The sub-goals include: *intellectual capital* or the market value of the non-financial assets; *human capital* or the value of company's people, their productivity, knowledge, skills, and experience; *structural capital* or the value of company's structure - internal and as it extends to customers and distributors, systems and works processes that leverage competitiveness; *customer capital or the* value of brand, relationships with customers, distribution channels, supply chain networks; and *organization capital* or value of the organization's capabilities, processes, intellectual properties, systems.
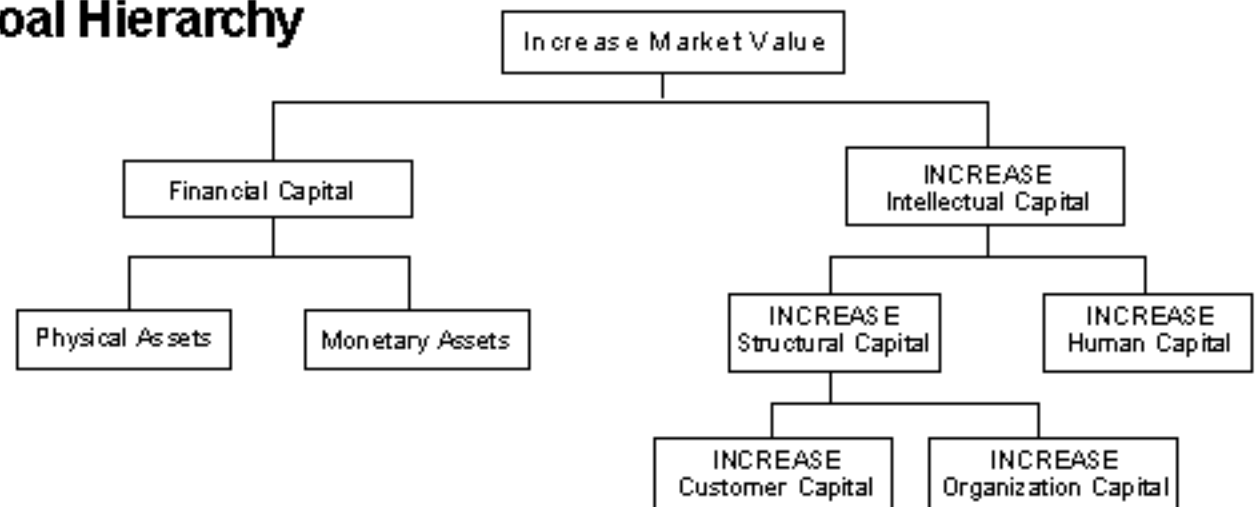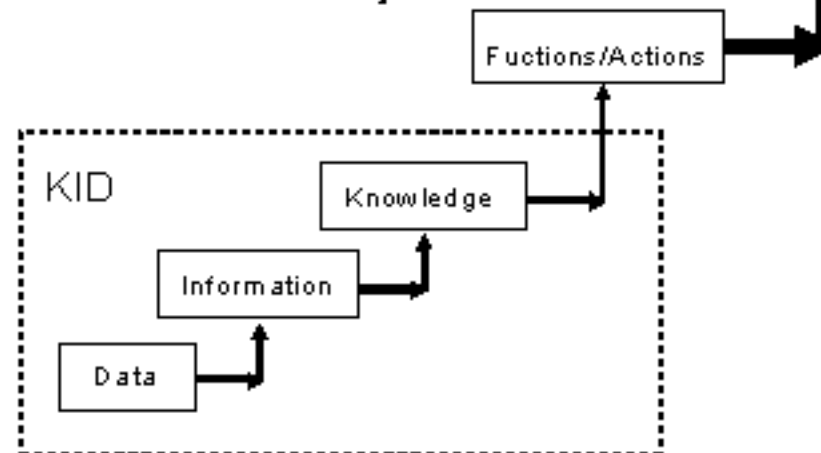
- ## DATA

  A **RECORD** to show the Revenue from customers

- ## INFORMATION

  A **TREND** to show the Revenue of Account A is continuously increasing in the past three months.

- ## KNOWLEDGE

  Account A released a new product three month ago, so they may need more of our products. We need a new marketing strategy

  Identify the **ROOT CAUSES** to explain why the Revenue of Account A is continuously increasing in the past three months, and how to keep the trend based on Diagnostics and Decision Rules interviewed from experts.
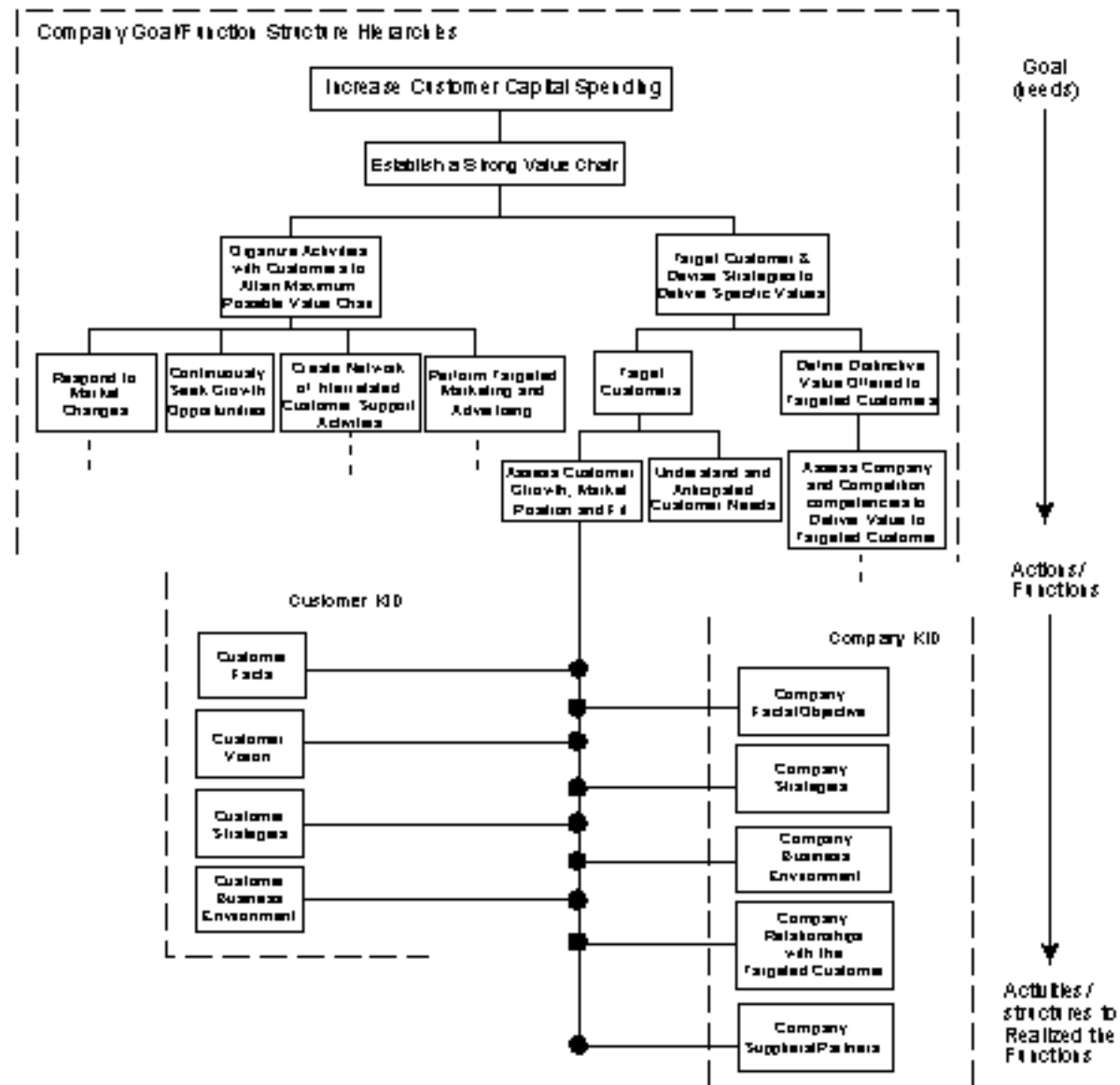
Know What/Who When/Where
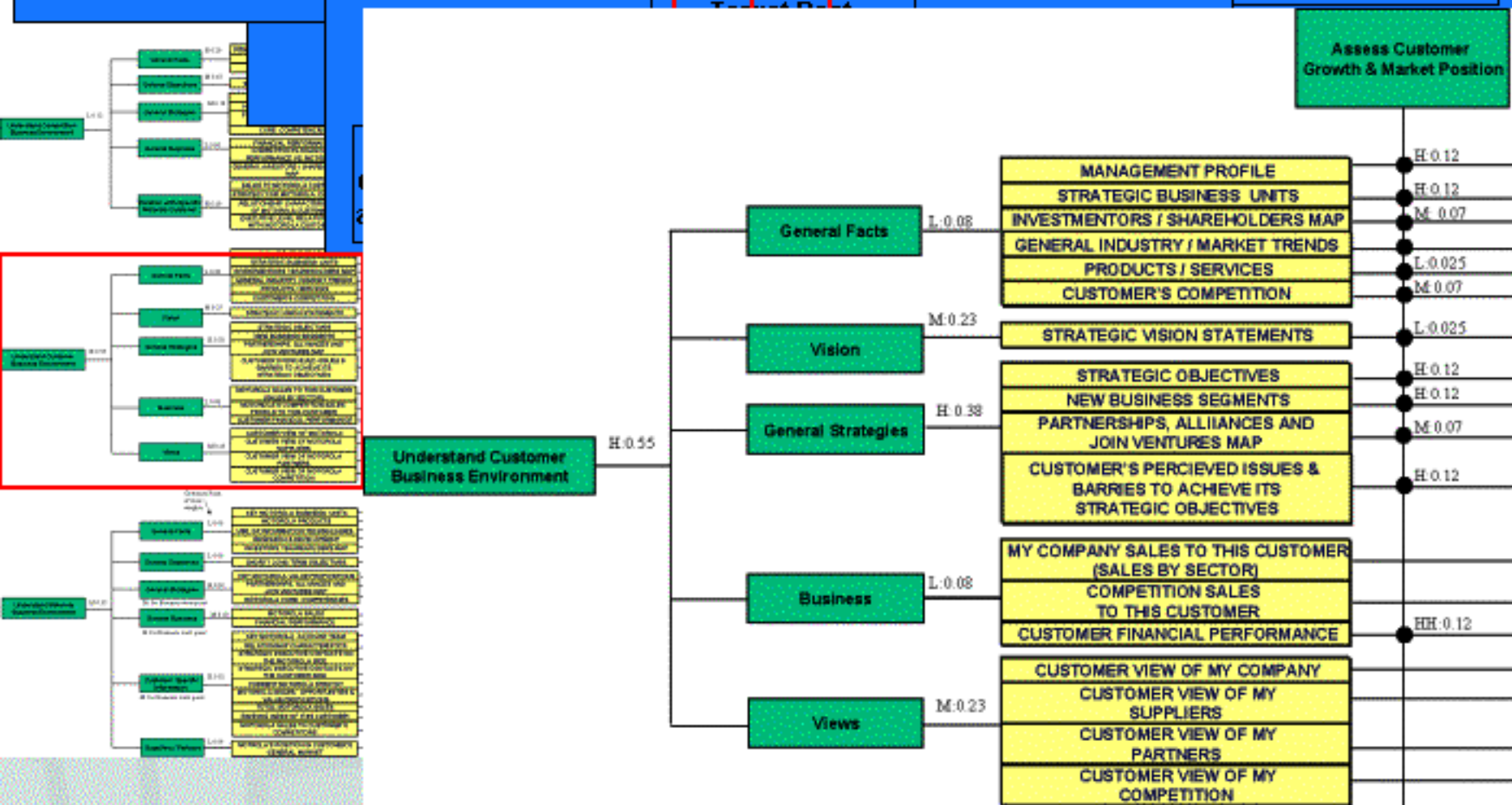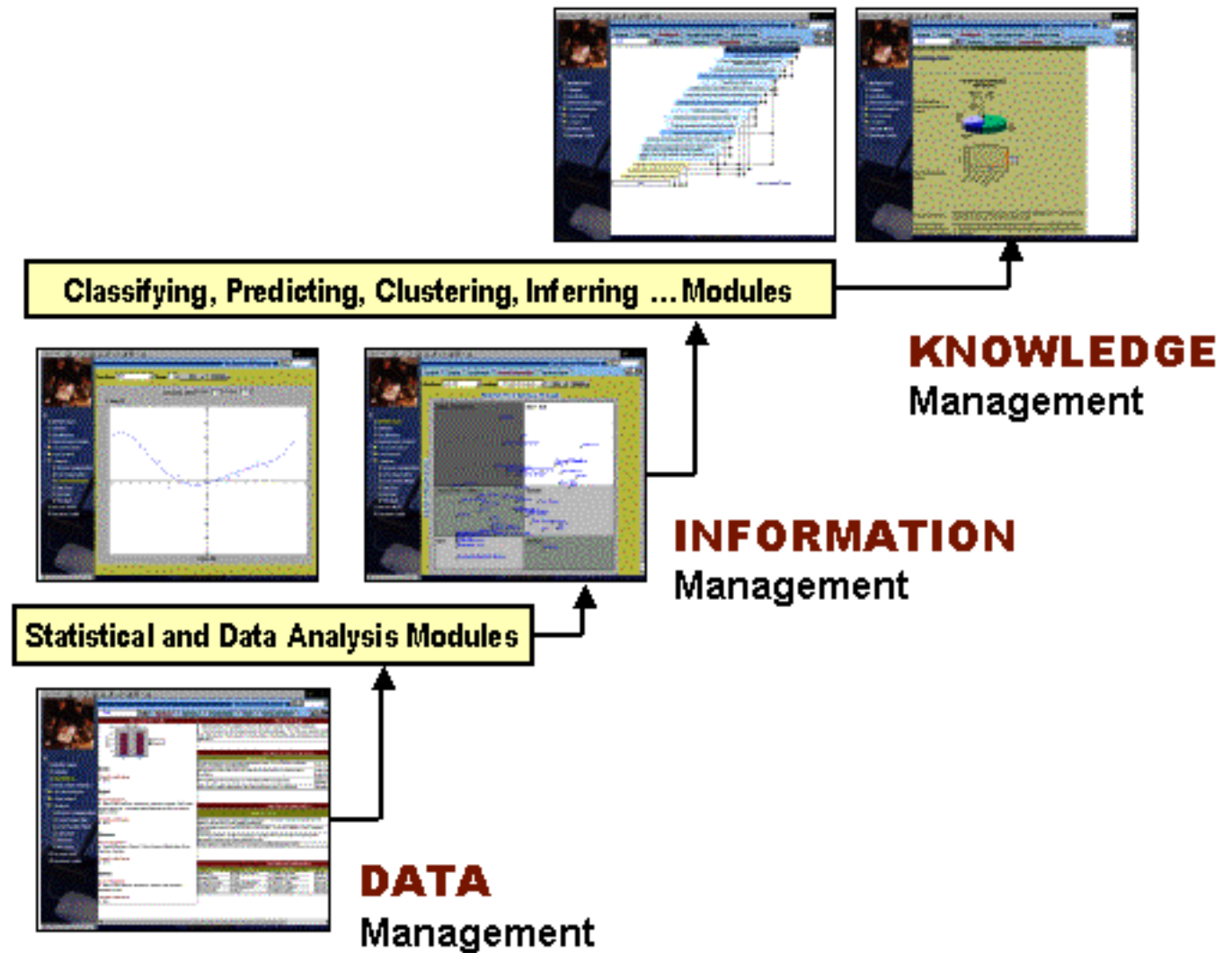
Know/ Why/ Know/ How

Maximize My Company's Performance & Growth
(Revenue & Profits)

Organize Activities with Customer to Offer the Best Value Chain

Target Customer & Have a Strategy to Deliver this Value Chain

Formulate a Broad Business Strategy

Assess Customer Growth & Market Position

Understand Customer Business Environment — H:0.55

General Facts	L:0.08
Vision	M:0.23
General Strategies	H:0.38
Business	L:0.08
Views	M:0.23

General Facts (L:0.08)
- MANAGEMENT PROFILE — H:0.12
- STRATEGIC BUSINESS UNITS — H:0.12
- INVESTMENTORS / SHAREHOLDERS MAP — M:0.07
- GENERAL INDUSTRY / MARKET TRENDS
- PRODUCTS / SERVICES — L:0.025
- CUSTOMER'S COMPETITION — M:0.07

Vision (M:0.23)
- STRATEGIC VISION STATEMENTS — L:0.025

General Strategies (H:0.38)
- STRATEGIC OBJECTIVES — H:0.12
- NEW BUSINESS SEGMENTS — H:0.12
- PARTNERSHIPS, ALLIIANCES AND JOIN VENTURES MAP — M:0.07
- CUSTOMER'S PERCIEVED ISSUES & BARRIES TO ACHIEVE ITS STRATEGIC OBJECTIVES — H:0.12

Business (L:0.08)
- MY COMPANY SALES TO THIS CUSTOMER (SALES BY SECTOR)
- COMPETITION SALES TO THIS CUSTOMER
- CUSTOMER FINANCIAL PERFORMANCE — HH:0.12

Views (M:0.23)
- CUSTOMER VIEW OF MY COMPANY
- CUSTOMER VIEW OF MY SUPPLIERS
- CUSTOMER VIEW OF MY PARTNERS
- CUSTOMER VIEW OF MY COMPETITION

KNOWLEDGE
Management

Classifying, Predicting, Clustering, Inferring ...Modules

INFORMATION
Management

Statistical and Data Analysis Modules

DATA
Management

- Systems get complex over time and space according to an evolution-based framework considering a neo-Darwinian approach

- Characteristics of complex systems defined and a modeling framework proposed

- Information technology making modeling of complexity a reality

- Several examples exists one in the business environment discussed