Research methods: systems approach
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The systems approach, which is also called the holistic or top-down approach, is a complementary approach to the conventional scientific or reductive (bottom-up) approach described in an earlier session. It is not meant to replace the reductive approach. The systems approach started to develop only in the 1950’s, including systems analysis and systems engineering. It is not yet at all complete due to challenges met. An ordinary set is a collection of objects classed together and having a common property, but a system is a set of parts so related as to form a whole with a certain purpose. We will present two architectures of systems called hierarchical (or serial) and network (or parallel) architectures. Most man-made systems are hierarchical and modular with a minimum number of interfaces between modules. (Continued)

(Continued) The fundamental system resources include material, energy, information, and capital. The aim of a designer is to use those resources as efficiently as possible. It is known that optimization of separate parts does not necessarily result in an optimal system. The efficiency is measured by performance metrics, which are also called performance criteria or performance measures. Systems are difficult to analyze because of the many interacting parts. On each hierarchy level there are some emergent properties that come from the interactions and they cannot be easily explained. Some deterministic systems are even chaotic unless they are designed carefully. The design of systems is not completely sequential but highly iterative. Some examples of fundamental problems will be briefly described.
Summary of my lectures

- A doctor must be able to discover new scientific knowledge independently (lecture 1)
- Existing knowledge in the literature is best found through bibliographies, citations, and databases (lecture 2)
- All documents are written using a hierarchical top-down approach (lecture 3)
- The actual research is a learning process where the opposite bottom-up approach (reductive approach) is used (lecture 4)
- Also top-down approach (systems approach) can be useful to foster creativity and support learning (lecture 5)

Research methods: systems approach

- Introduction
- Reductionism and holism
- Basic resources
- Open problems
- History and roadmaps
- Conclusions
- References
Introduction

Balloon in a Car

- What happens to the helium balloon?
Technology: Natural Science and Engineering

- Ecosystem
  - Organic nature
  - Inorganic nature
- Technosystem
  - Human beings
  - Society
  - Products/services
  - Waste

Science
- Energy
- Materials/laws

Engineering
- Humanities
- Social science

Sciences, Practices, and Technology
- [Wilson99], [Schwanitz99]

<table>
<thead>
<tr>
<th>Humanities (human culture)</th>
<th>Practices</th>
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<tbody>
<tr>
<td>• philosophy</td>
<td>• political science</td>
</tr>
<tr>
<td>• history</td>
<td>• jurisprudence (“science of law”)</td>
</tr>
<tr>
<td>• study of literature</td>
<td>• pedagogics</td>
</tr>
<tr>
<td>• philology (linguistics)</td>
<td>• communications theory and mass media</td>
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Social science (people within society)
- • economics |
- • sociology |
- • psychology |

Science (natural science)
- • biology |
- • chemistry |
- • physics |

Formal science
- • computer science |
- • set theory |
- • mathematics |
- • logic |

Technology
- • medicine |
- • agriculture |
- • engineering |
What a System is [Hall62]

- **System** is a set or arrangement of things so **related or connected** as to form a unity or organic whole (for example, the solar system)
  - a set of parts with relationships between the parts and between their properties
- **Desirable subjects for a systems engineer:** probability and statistics, philosophy, economics, psychology, language
Set-member and part-whole relations [Honderich05]

- A **whole** consists of parts, properties, relations, and events.
- A **process** is a series of changes with some unity or unifying principle (time is the dimension of change).

Reductionism and Holism [Checkland99], [Honderich05]

- **reductionism**: theory that every complex phenomenon can be explained by analyzing the simplest, most basic physical mechanisms that are in operation during the phenomenon (**scientific approach**)
- **holism**: theory that whole entities have an existence other than as the mere sum of their parts (**systems approach**)
  - **emergence**: occurrence of properties at higher levels of organization which are not predictable from properties found at lower levels [Nagel79], for example transparency of water, temperature of a gas
Classification of Systems

- Systems are divided into two classes [Pagels88]
  - Hierarchical systems (most engineering systems, serial organization)
  - Network systems (there is no top and bottom, much redundancy, parallel organization, for example brain)
- Our analytical tools are not valid in complex systems [Bertalanffy98], [Pagels88]
  - Properties of a system depends on the parts and their relations (“everything depends on everything”, for example three-body problem in physics, two-body problem corresponds to a feedback system)
- Complex systems may have a chaotic behavior

Product Life Cycle (1) [Belliveau02]

- Consumer needs
- Product requirements
- Product concept
- Product specifications
- Purchase/implementation/manufacturing
- Distribution/Marketing
- Installation/Operation
- Maintenance
**Product Life Cycle (2) [Belliveau02]**

- **Product requirements** (translation of customer needs into technical terms)
- **Product concept** (description of the technology, primary features, and form of a product)
- **Product specifications** (description of a product to be designed which operates in the environment specified in the product requirements)

**Performance [Bock01], [ame03], [ISO Guide 99]**

- **Performance metric** is a function (for example mean-square error) of a quantity whose output is performance value
- **Performance value** or **performance** is the numerical value of the performance metric, to be compared with the performance requirement
- **Performance requirement** is desired performance value that describes some user need
Trueness, Precision, and Accuracy, [amc03], [ISO Guide 99]

- Trueness (small systematic error)
- Precision (small random error)
- Accuracy (small total error)

Uncertainty [amc03], [ISO Guide 99]

- Each statistical measurement result should be presented with three numbers: 1) average, 2) confidence interval, and 3) confidence level [Kreyszig83]
Accuracy and uncertainty [amc03], [ISO Guide 99]

Accuracy: the closeness of agreement between a measurement result and the accepted reference value (the accepted true value of the measurand), includes the terms trueness and precision, expressed with uncertainty.

Trueness: the closeness of agreement between the average value obtained from a large series of measurement results and the accepted reference value, includes systematic errors only.

Precision: the closeness of agreement between independent measurement results obtained under stipulated conditions, includes random errors only.

Uncertainty: parameter that characterizes the dispersion of the quantity values that are being attributed to a measurement, includes systematic and random errors, expressed for example with standard deviation (if known systematic errors are first removed), or confidence interval (coverage interval in ISO terminology) and confidence level (coverage probability in ISO terminology).

Resources are Converted into Properties (1) [Checkland99], [Honderich05]

- **Performance** is the manner in which something reacts or fulfils its intended purpose, measures the efficiency in using the basic resources.
- **Complexity** refers to the number of parts and their relations, measured by the amount of used resources.
Resources are Converted into Properties (2)

![Diagram showing the conversion of resources into properties](image)

Analysis, Simulations, and Experiments (1)

![Diagram showing the process of analysis, simulation, and prototype](image)
Analysis, Simulations, and Experiments (2)

1. Mathematical analysis (theoretical model)
   - creates best scientific papers
   - simple, mathematically tractable problem, must be often linear (numerical results needed)

2. Simulations (numerical analysis of the theoretical model)
   - complicated systems can be developed rapidly, but slow to simulate
   - basic idea: lower level blocks are simplified and idealized (hierarchy)
   - key problem: realistic models for the environment (e.g. channel)

3. Prototyping (empirical research)
   - more convincing than “pure” simulations, not so flexible, slow and expensive to develop complicated systems
   - environment (channel) simulators still needed (approximations!), field tests expensive, repeatability?

Building a Prototype

- Build the prototype from **complete components**
  - as high integration as possible
- Build a **focused prototype** instead of comprehensive prototype [Ulrich95]
  - demonstrate the novel properties
- Build a **scaled prototype** [Honderich05]
  - macroscopic or microscopic (miniature) model
  - example: use 100 Hz instead of 1000 Hz (time scaled down by ten, spatial dimensions scaled up by ten)
- Build a **virtual prototype**
  - simulation models are time-scaled models
Verification, Validation, and Certification
[Calvez93], [ISO Guide 99]

- **verification** is establishing the truth of a hypothesis, usually by experiment or observation (in science), confirmation that a system fulfills the specified system requirements, or a design step satisfies the requirements of the higher hierarchy level in a laboratory environment.

- **validation** is confirmation that the system fulfills the requirements for a stated intended use (in the field), i.e., verification of system requirements that may be incomplete, or confirmation that a design step satisfies the requirements at the same hierarchy level.

- **certification** is an external validation given by an accredited authority.

Order: Sequential Process [Bohm92]

- Sequential process is characterized by a regular sequence of events [Bohm92], [Honderich05].
- In project design this kind of process is called the waterfall model where the project is divided into rather independent phases [Calvez93], [Leppälä03].
Order: Iterative Process [Bohm92]

- Iterative or generative process is an overall process from which the manifest form of things emerges creatively, internal interrelations are included, especially iterations.
- In project design this kind of process is called **spiral model**: the whole process is repeated and each time the result improves [Calvez93], [Leppälä03].
Different Hierarchies

Description Levels

- Functional level
- Behavioral level
- Executive level

Nested Hierarchy

Layered Pattern (Successive Layers)

Description Levels [Calvez93]

- **functional model** a structural (topological) model where a structure is built using functions and relations between them
- **behavioral model** a model which describes the behavior of internal functions of a system, specification of algorithms for the functions
- **executive model** implementation model that specifies the physical parts of the system, consisting of processors, memories, and communication nodes
- An alternative description in three domains: **structural domain**, **behavioral domain** and **physical domain** [Gajski88]
Nested Hierarchy [Checkland99]

- Levels mentioned in [Gajski88] from bottom to top: circuit, logic, microarchitectural, algorithmic, and system level

Layered Pattern [Tanenbaum96]

- Open Systems Interconnection (OSI) model inc. (from bottom to top) physical layer, data link layer, network layer, transport layer, session layer, presentation layer, and application layer
- Each layer produces a coherent set of services to the upper layers through a public interface (lower layers seldom use upper layers and these exceptions must be carefully documented)
- Advantages: support for standardization, dependencies are kept local, exchangeability, maintainability, and portability
Summary of Design Hierarchies

- Successive layers
  - Top
  - Bottom
  - Nested hierarchy levels

- Description levels
  - Top

- Systems engineering
  - System models, relationships, complexity analysis

- History & roadmaps
  - Reviews of literature

- Fundamental limits
  - Physical limits, optimal systems, performance analysis

What is Guiding Our Work
Fundamental Limits (about 1850-1950)

- second law of thermodynamics (Carnot, Clausius)
- absolute zero (Kelvin)
- upper velocity limit (Einstein)
- uncertainty principle (Heisenberg)
- incompleteness theorem (Goedel)
- speed of transmission of intelligence (Nyquist)
- channel coding theorem (Shannon)

Refs. [Lundheim02], scienceworld.wolfram.com

Some Fundamental Engineering Problems

- Problems: Distribution of information, energy, materials, products, and services, transportation of people, waste management, etc.
Some Open Problems in Engineering

- General theory of systems (philosophy of technology, hierarchy theory) [Checkland99]
- Semantic information theory (Shannon’s statistical information theory does not cover the meaning of the information, only the amount of information) [Checkland99]
- Network information theory (statistical information theory covers only isolated links) [Cover91]
- Frame problem (how a machine could decide the frame of reference or context) [Honderich05]

Fundamental Problems in Information Engineering

- Problems: Transferring, storing, processing and displaying of information, storing of energy, etc.
Why are Some Design Problems Difficult to Solve? [Michalewicz04]

- no single performance metric that describes the quality of any proposed solution is available, but a set of performance metrics that should be weighted
- the number of solutions in the search space is so large as to forbid an exhaustive search for the best answer and the iterative methods (by trial and error) are too slow or unreliable to find the optimum solution
- the possible solutions are so heavily constrained that constructing even one feasible answer is difficult (reduction is used to simplify the problem and this adds an additional constraint)
- the performance metric is noisy or varies with time (need an entire series of solutions)
- our models may be too simplified so that any result is essentially useless
- some psychological barrier prevents us from discovering a solution

History

- Internet and hypertext (rotating book mill against the flood of books, Agostini Ramelli, 1588)
Example: History of Telecommunications

[Haykin01], [Proakis01]

VTT TECHNICAL RESEARCH CENTRE OF FINLAND

Cultural History [Boyer91]

VTT TECHNICAL RESEARCH CENTRE OF FINLAND
Legends (see previous page)

- - -

Greece

Rome

Europe

End of ancient science (Academy closed)

Europe

1088
First university (Bologna)

1620

1632

1637

Start of modern science (Bacon, Galilei, Descartes)

Indian-Arabian numbers to Europe

- - -

Arabia

Arabian calendar

Omar Khayyam dies

Roadmap and Vision (for details of roadmaps, see [Kostoff01])

Basic research

Applied research

Cognitive networks

Haptic interaction

Mobile video

Mobile wide-screens

Tele-immersion

Multisense interaction

Mobile Internet

Mobile televisions

Multimedia convergence

Mobile video

High-definition wide-screens

Multicast

Mobile universal (UMTS+advanced)

Digital cellular phones

Wireless Internet

Positioning

Ad hoc networks

Wireless local area networks

Digital broadcasting

GPS

MAS

SMS

Camera phones

2000

2005

2010

2015

2020

Commercial exploitation
Tele-Immersion
(graphics.cs.brown.edu/research/telei/home.html)

- We define tele-immersion as that sense of shared presence with distant individuals and their environments that feels substantially as if they were in one's own local space.
- This kind of tele-immersion differs significantly from conventional video teleconferencing in that the user's view of the remote environment changes dynamically as he moves his head.

Vision of Telecommunications
(mostly science fiction)

- Telesocializing?
- Telepathy?
- Worm holes?
- ANSIBLE?
- Intergalactic network?
- Quantum comms?
- Teleportation?
- Time machines?
- Direct MMI?
- Nanobots?
- Holodeck?
- Real-time Internet?

3000 4000 5000 6000 7000
Comments to Roadmap and Vision [Clute95]

- **direct man machine interface (MMI)** refers to a direct wired interface to human brains
- **haptic interaction** refers to the sense of touch, **multi-sense interaction** refers to all the five senses
- **holodeck** refers to telepresence and virtual reality combined: all involved are in a virtual environment
- **nanobot** is a small robot moving in human brains and controlled wirelessly, it makes wireless direct MMI possible
- **telepresence** refers to presence in an existing environment for example as a hologram; it does not need glasses, but it needs a material (for example water vapor) to which the hologram is projected
- **teleportation**: the theoretical portation of matter through space by converting it into energy and then reconverting it at the terminal point
- **virtual reality**: computer-generated simulation of three-dimensional images of environment or sequence of events that someone using special equipment (glasses, dress) may view and interact with a seemingly physical way
- **worm hole**: a hypothetical space-time tunnel or channel connecting a black hole with another universe
- **quantum communications** refers to teleportation of quantum states

Researcher’s Checklist (1)

- **Funding**, **project plan**, **time schedule**, needed **competence**, related areas, **analogies**, measurable milestones after some months, rough results for each year
- **Motivation**, also long-term motivation, applications
- **Problem** and rough **competing hypotheses**, which are refined iteratively, fundamental problems preferred
- **Performance metrics** for both performance and complexity
- **Reference results** (trivial cases, complete data with optimal processing, earlier solutions, benchmarks), **confidence intervals** for statistical results
- **Literature review**, landmark books and papers, hierarchical classification of ideas, keywords, databases, good authors
- **System model**, a priori knowledge, **block diagram** to show division into parts and relationships, idealizations, linear or nonlinear model, **parameters**, hierarchy and modularity
**Researcher’s Checklist (2)**

- **Bottom up** approach, from simple towards more complicated, reduce the problem into simple idealized and separate subproblems, make experiments (empirical-inductive approach preferred), remove nonidealities (distortions, interference) step by step, present results **top down** (hypothetico-deductive approach)

- **Discussion via** brief **technical reports**, which are revised, good **organization**, good grammar, concise and accurate text, clearly defined terms

- **Publications**, novelty, significance, correctness, readability, 1-2 good conference papers per year, 1-2 journal papers after three years

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**Conclusions (1)**

1. **Idea**
2. Literature review
3. Problem and hypotheses
4. Experiments/analysis
5. Theory/paper (new knowledge)
6. System (prototype)
Conclusions (3)

- use **bottom-up (inductive) approach** in research, which is essentially a learning process
- use **top-down (deductive) approach** in technical documents (reviews, monographs), this will make the presentation compact and easy to follow for experts (use IMRAD structure)
- use bottom-up approach in teaching (tutorials, textbooks), and integrate results by using the top-down approach
- remember that a doctoral thesis is not a textbook (writing a textbook is a large challenge), write the thesis for experts in the field
Conclusions (4): Iterative research method

Conclusions (5): Theory and practice

- A good research project emphasizes theoretical results (usually system models) and uses prototypes for verification and validation of the new results.
Conclusions (5): Theory and practice

- 1) In mathematics we use Hilbertian axiomatic systems (*coherence* important), 2) in science and engineering we use hypothetico-deductive systems (*coherence and correspondence* with reality important)
- Do not mix these two axiomatic systems: location of hypothesis is different (most theories in science and engineering are based on theoretical models, but axiomatic system is an ideal form of theory).

Final conclusions

**General hints**
- use bibliographies to improve your efficiency in literature reviews (start from books and reviews, see the introduction of original papers)
- learn the terminology, write a *classification* (*taxonomy*) for the state of the art, and see historical trends
- define a problem and hypotheses (use *bottom-up empirical-inductive approach*, make experiments early in your project)
- start to outline the paper right from the beginning (there will never be “more time”), emphasize good organization, use *top-down deductive approach* in documents
- reserve time for all phases in your project plan
Final Word: Focus

“General Groves -- asks Oppenheimer [the leader of the Manhattan project that developed the atomic bomb] -- what it will take to get the Gadget [atomic bomb] built. “Focus,” Oppie answers, naming a critical element at every Great Group.” [Bennis98]

Source of the figure: Associated Press (http://www.infoplease.com/spot/mm-beamon.html)

References (1)

References (2)

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References (3)

References (4)