How to do Scientific Research on Engineering and Technology?

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Kari Leppälä- CV

- Education: 1974 M.Sc (electronics engineering) TKK, Helsinki; 1994 Ph.D (industrial engineering & management) univ. of Oulu; dissertation on project management in R&D.
- 1974 –1982: Strömberg Ltd, Afora Ltd, Helsinki (programmer, system analyst, head of design office) ; automation projects for sawmill and paper industry
- 1982- 2000: Technical Research Centre of Finland, Oulu
  - research on computer architectures, real time systems, project management and innovations
  - managing and coordinating contracted R&D projects
  - projects and coordination work for the Finnish space programme
  - Quality manager of VTT electronics; main author for VTT’s Project Guide.
  - Evaluator for EU projects. Space technology transfer program coordinator.
- 2001 –: Provisec Ltd. CEO, leading consultant (development of processes for project management, quality management, R&D; training; teaching at university).
- Publications: > 100 technical and scientific papers; patents; principal author of "Virtual Design of Smart Products" (EDITA 2003)
- Interests: Innovations and technology, R&D processes, philosophy of technology
Some conventions in my presentation

• According to the German and Scandinavian tradition I use “science” in its most general meaning: covering all branches of natural sciences, humanities, medicine and economy.

• I also address technology in a broad sense: 1. the tradition of promoting, developing and managing living conditions by different artificial tools, materials, objects, methods etc. 2. the modern, post-Galileo technology, applying methods of science (a more accurate definition will be given in the text).

• My text is addressed primarily to doctoral students preparing their thesis on some technology-related subject. Some students may even have professional expertise on engineering. The common factor is that their education has been engineering-oriented. Engineering is a practical skill. Making science is another kind of skill – and I try to show that it is practical, too. Actually it is a practice.

Student in practical work..

Many doctoral students in technical faculties are working on technical tasks, like design and system development. It is only natural that students are enthusiastic in using their skills to achieve concrete results. Typically the results of such work are design documents, design reports, prototypes and so on.

What is the value of those results regarding the dissertation? Does design have some scientific value?

How to perform such work, in order to include it as material of the doctoral thesis?
University in practical work…

Modern technology utilizes methods and results from science. On the other hand, the core of technology is its making – design. Technical faculties and universities are teaching basic sciences, technical sciences, and methods and practices of designing, manufacturing and industrial management. In addition, they conduct scientific research.

Can the student navigate in this world of different ways of knowing and doing?
Should he choose between scientific and practical orientation; and once the choice is made, could it be changed?
There is a lot of talk about “top units” and performance and rank of universities. What does this really mean?

Content of the lecture

- Preliminary assumptions
- Science as I see it
- Nature of technology
- The science of technology
- Typology of technical science papers
- Reading
Preliminary assumptions

Let’s face some crude facts

- Technology is not the same as science – they are different and separate, although they interact
- Technology and science have different objectives
  - Science aims at new information, technology aims at utility
- Technical documents, like system descriptions, design documents and manuals have no scientific value as such
  - No more than any arbitrary real life object
- Still: it is the task of universities to teach and promote also practical methods and skills on advanced topics
  - Some faculties/universities are teaching practical skills (technology, medicine, economy, management…)
  - Those faculties/universities are and should be also active on scientific research
Some fields of human activity

- There are numerous fields of human activity
  - each field is related with knowledge, information, behaviour patterns etc.
  - each field has internally set objectives and some means of developing itself
  - fields have traditions for judging what is valid and what is not valid
  - science and technology are no more or less than human activity fields
  - they are different and distinct – but they do interact

Science as I see it

- although science and scientific methods have already been discussed by other speakers, it is useful to discuss, as there is no “standard” definition
Philosophy fundamentals in 15 seconds

- What is the principal problem of philosophy?
- How can we get reliable information about the world!!
- Position and mission:
  - the world possesses enduring, real properties and qualities, which do exist objectively - regardless of human comprehension or attention
  - we may try to find out about them, although it may be very difficult, because of our limited capacity as humans
  - science is a (proven) systematic way to find out things !!!
  - it seems to be, that the nature is inexhaustible: the well of information is infinitely deep

One “definition” of science:

1. Science is a collection of claims regarding the nature of things
   - a static view
   - These claims are documented and justified
     - but they are not proven, final or eternal
2. Science is the process, which collects, investigates and publishes those claims
   - a dynamic view
   - All scientific information is in documents
     - journals, books, or other forms of publications
     - this information is accessible for anybody (at least sooner or later)
     - there is also a large and continuously growing and open supply of observations (data) just waiting to be analysed (like data archives from space probes and physics research facilities, meteorological data, data banks of numerous other organisations)
   - Science is created and regulated by the science community
The science community

- The science community decides what is valid and what not
- The science community is a unique formation
  - it is completely open for every one on the earth
  - working principle: publication in journals and conferences, and open criticism
  - all relevant information is public
  - there are no priests no guards, no censorship – and no formal membership
  - there are no written rules – but many unwritten ones
- So this is the ideal, and there are some practical hints…
  - you are more credible if you get a PhD
  - select an efficient forum – a respected journal or conference
  - you may violate traditions – but do it openly and explain why you do it
  - be absolutely honest – forgery kills a scientist
  - respect and honour your colleagues – and you will be respected

The grand traditions of scientific thinking

1. Aristotelean:
   - reasoning and human intellect as the main source of information
   - aims for final explanations: “why”
   - accepts different viewpoints; holism
   - typical application areas: social sciences, humanities: Europe, catholic culture

2. Galilean:
   - interaction between theories and observations
   - aims for causal relations: “how”
   - reductionism; ultimate goal reduction to basic physics
   - typical application areas: sciences and medicine; Scandinavia, USA; protestant culture
Scientific revolution was initiated by Galileo

- Galileo Galilei (1564-1642) is known for his struggle against the church to defend the new world order.
- He revolutionized science by creating and testing hypotheses, making planned and exact experiments, using instruments like telescope to improve human senses, making unheard astronomical findings, and describing laws of nature by mathematics.
  - (He did not use compact formulae, but reported the results using long verbal and logical proofs)
- He employed thought experiments
- He used inclined plane to slow down movement (use of laboratory conditions)
- He created "new sciences": kinematics, hydrostatics, strength of structures
- He made inventions (military calculation device, improved telescopes, law of pendulum and pendulum clock)
- The Galilean method is in wide use in research of nature and in technical sciences

Some common features of scientific method:

- Gradual refinement of the problem and solution (Hans Reichenbach)
  - discovery (pre-hypothesis, methodological fumbling)
  - justification (clarification of hypothesis; proof or support of hypothesis)
- Falsification (Karl Popper)
  - even a large number of supporting observations cannot prove a hypothesis
  - even a single negative observation will falsificate it (Goodman’s paradox)
- Need of intuition
  - there is no "meta-theory", which tells how to invent the hypothesis or how to find a proof for it
- Prediction (Hempel-Oppenheim model)
  - a theory, which explains past phenomena or behaviour, should also be able to predict future ones
Theories of truth

Methods for proving or refuting hypothesis depend on the research tradition on each particular science branch.

Truth theories are universal! They do not work on the level of single papers, but rather on discipline and community level.

Proposed theories:

- **Consensus**
  - common opinion among colleagues / community (beware: million flies…)

- **Pragmatism**
  - if theory can be applied, it is valid (typical proof of a technical artefact)

- **Coherence**
  - what seems to fit in the big picture

- **Correspondence**
  - a theory is valid if there is a structural 1-1 correspondence between a model based on the theory, and its object in the real world

Paradigm and crisis

- **Thomas Kuhn: "Structure of scientific revolutions"**:  
  - Science is in "normal phase", or in "crisis"  
  - In the normal phase, scientific work supports the dominating paradigm  
  - In "crisis", the current paradigm is no longer satisfactory: sooner or later it will be replaced by a better paradigm  
  - There is a contradiction: "normal science" brings very little new information, but a paradigm breaking approach will be rejected

- **Alternative and disputed conclusions from Kuhn’s theory:**
  1. Finalism: science is evolving towards a perfect and faultless ideal
  2. Relativism: one paradigm is no better than another: the only difference is in their application domains (example: Newton's physics is perfect for terrestrial kinematics, relativistic physics is mandatory in elementary particle research and astronomy)
The nature of technology

- And why it is different compared with science

The versatile technology

- Technology is the capability of the mankind to manage, improve and shape its living conditions, through application of self developed tools, devices, machines, materials and methods.
- Technology is typical for humans. Animals do not have technology- only behaviour patterns performed by instinct. Limited capabilities of producing artefacts like nests have been evolved together with the animal, while human technology is based on cultural evolution, and is extremely dynamic.
- Technology is intellectual, social and economical formation. Technology has emerged as sudden, steep and extremely rapid and radical changes, separated by tranquil periods. Examples of development steps are fire making, fishing, hunting, agriculture, building, transportation, communication, warfare, and organisational practices.
- The latest step in this sequence is scientific technology and industrial revolution.
Technology aims for utility

- Technology is instrumental. It consists of methods, practices and devices which are necessary for everyday life.
- Technology is embedded in life style. It is difficult to recognise and analyse because it penetrates everything we do.
- We learn our technology in culture, and living with it. There are different levels and objectives in mastering technology. Some tasks require training and specialisation.
- Man has an inherent need to manage and control his life and environment.
- In traditional societies everybody can use, control and maintain technology. Man has freedom to act and choose between alternatives.
- Industrial and post-industrial societies are based on specialisation. Everyman is alienated from technology.

A definition for technology (one of many):

- Technology is creative activity, which creates new forms and new information about those forms
- Technology is an inseparable part of everyday life (even the biology of man is sculpted by technology !!)
- Technology consists of: a. artefacts, b. procedures, c. information about application of a and b
  - this information is encoded in documents, in individuals, and in culture, and it is embedded in technical artefacts
Technology vs. science

- Technology is NOT:
  - applied science
  - not science at all!
- But:
  - technology utilises results from science
  - applies scientific methods
  - is an object of scientific research (like any human activity)
  - technology is an art of doing
  - technology is a pervasive element in modern society
  - technology has strong social and cultural context
    (so that we have difficulties in seeing it)

Science and technology as processes

INPUT

PUBLIC

PRIVATE

OUTPUT

PUBLIC

PRIVATE

SCIENCE

TECHNOLOGY

artificial object

artificial object

Information

Information

Information

Information
Leonardo – the great engineer

- Renaissance masters created architecture and engineering as visual art and craft
- Leonardo used his pen as his instrument, to explore nature (anatomy, structures, turbulence, human psychology), and to create artificial and even future machines and other constructs.
- He was curious about everything. A decisive attitude of scientists at a time when science was in infancy.
- He made experiments but was too restless to control the experiments. His creativity in paint chemistry nearly destroyed many great paintings.
- Engineering is still visual art. The French revolution and Gaspard Monge replaced Leonardo's drawing style with descriptive geometry - still applied in engineering drawings.

How engineers study and justify their creations

- evolution of methods

- artistic drawing
- 3D computer graphics
- full prototyping
- partial prototyping
- scale models
- descriptive geometry
- graphical notations
- virtual prototyping
- Language (story, logic)
- analytical & formal models
- computer simulation
Difference in scientist’s and engineer’s work processes

- Technology aims for a new artificial object or a new application – science aims for new information
- Scientists read and write a lot – engineers work with local information and local culture
- Scientist’s world is open and global – engineer’s world restricted and local
- Regarding science about technology, involvement with private and restricted information possesses some problems
  - These problems are overcome by disclosing some information from scientific papers: like the source of information, or exact application
  - Examples: company names in a method study are not told; product names or details of a usability study are not given.

The science of technology
Is there a science of technology?

- "Sciences of the artificial" (H. A. Simon 1981 Nobel prize in economy):
  - there is no unified science of technology
  - there should be one!
  - it should integrate design science with the science explaining artefacts
  - (also Karl Popper considers, that the artificial has a special character)

- Following Simon’s reasoning, we can describe, what the science of technology does:
  - it analyses, explains and models engineering and manufacturing processes
  - it explains and predicts properties and behaviour of artificial objects
  - it addresses interactions associated with manufacturing, adoption and utilisation of technical artefacts: from e.g. individual's, organisation's, community's, economy's and nature's viewpoints

Examples of technically oriented science

- Applying methods of natural sciences – for example physics
  - research on new algorithms (very close to mathematics)
  - strength of materials (material physics)
  - circuit theory (physics)
  - telecommunications (mathematics, physics, information theory)
  - theory of solid state components (physics, material physics, chemistry)

- Applying humanities and social sciences
  - programming theory (mathematics, cognitive psychology, linguistics)
  - usability research (cognitive psychology, experimental psychology, linguistics, ergonomics)
  - innovation research (sociology, economy, psychology, ergonomics)
  - design methods (cognitive psychology, mathematics, linguistics)
Three main categories of scientific papers about technology:

1. Research about the nature (ontology) of technical artefacts
   • ordinary engineering sciences (statics, dynamics, theory of strength, circuit theory, communication theory, electricity, chemistry…)
   • modelled according to theories of nature, i.e. physics
2. Research of design and manufacturing
   • very rich family of possible approaches
   • i.e. according to psychology, sociology, linguistics, ergonomics..
3. Research of interactions in use, utilisation or adoption of technology; research of impacts of technology
   • even more approaches (psychology, cultural impacts, environmental impacts, economical effects…)

Criteria and method examples
Some quality criteria of dissertations

- Novelty; new information
  - The results are new, something which has not been known before.
- Relevance
  - The research problem is important, worth knowing
  - The study is made with appropriate methods and diligence.
  - References are up-to-date and related with the subject of study
- Design of the study
  - Clarity of problem statement, selection of methods, presentation of results
- Quality of results
  - Results are identifiable, and serve the purpose of the study
  - The research problem is solved, for example the hypothesis is proved or refuted.
    Or: the reason why it could not be solved is made clear
  - Conclusions are based on facts only

Methods of ontology type studies

- Ontology papers study the nature of technical artefacts
- Method framework is similar to science…
  - Mathematics, physics, chemistry
- .. or to technical sciences
  - Circuit theory, communications theory, tribology…
- Typically the author creates a model for some technical artefact
  - The model may focus on some property, like performance, quality, reliability, behaviour..
  - The model is validated by analysis, simulations or experiments
- Boundary conditions may become important
  - Physical phenomena takes place in closed volume
  - Numerical methods are typical to overcome complexity
- Qualitative properties are challenging
  - For example: “flying qualities of an airplane”
Studying creation of technology

- **Design science approach**
  - Efficiency of methods and tools; performance of design teams; psychological factors
  - Managing the design process; managing requirements, technologies, costs, manufacturability; other constraints.

- **Industrial management approach**
  - Technology-business interactions; strategy issues
  - Networking issues
  - Managing engineers, processes, quality
  - Managing competence and knowledge

- **Manufacturing approach**
  - Processes, machinery
  - Logistics, material and energy flows
  - Design-manufacturing interface
  - Agility, flexibility

Studying use, adoption, impacts

- **End user and consumer issues**
  - Usability studies, ergonomy, need analysis, customer support and service

- **Social and society issues**
  - Impact of technology on group behaviour; sociology; political issues

- **Innovations and infrastructures**
  - Diffusion of technology; innovation dynamics; success stories and failures
  - Evolution and control of service sector, education and training

- **Economics and management**
  - Development of companies and industrial sectors

- **Environment**
  - Technology as hazard and load; technology as monitoring and problem resolution device
Supplementary reading


4. Eco, Umberto. Oppineisuuden osoittaminen. [Many practical advises; like selecting of subject and use of references. English translation not available]

5. Kuhn, Thomas. 1962. The structure of scientific revolutions. Chicago: The University of Chicago Press. [Dynamic nature of science; open to interpretations]


