How to do Scientific Research on Engineering and Technology?

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Kari Leppälä- CV
(how do I know what I know)

Education
1994: Ph.D (industrial engineering & management) University of Oulu;
1974: M.Sc (electronics engineering) Helsinki university of technology;

Experience
2011 – Senior mentor, CxO Oy
2001 – : Provisec Ltd. CEO, leading consultant (innovation and technology development processes, project management, quality management, R&D; training; teaching at university).
1982– 2000: Technical Research Centre of Finland, Oulu; research on computer architectures, real time systems, project management and coordinating contracted R&D projects. Projects and coordination for the Finnish space programme; Evaluator for EU projects; VTT ´s Project Guide; Quality manager of VTT electronics

Other issues:
> 100 technical and scientific papers; patents; author: "Projektitoiminnan musta kirja" (Readme.fi 2011). principal author & editor: "virtual Design of Smart Products" (EDITA 2003)
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. Utilization of methods of science, to promote development and application of technology.
- My text is addressed to doctoral students preparing their thesis on some technology-related subject. They may have engineering-oriented education; some are even professional engineers.

Engineering is a practical skill. Making science is a very different skill. How to combine these skills to a credible scientific contribution?

Problems with technology related research papers

- Students in technical faculties study mathematics and engineering, and are insecure with scientific thinking.
- "30 to 50 % of software papers lack any type of empirical validation"
- Few research papers are strictly formal in a mathematical sense (which would allow analytical validation)
- Many studies are like design reports. What is their scientific contribution? (should be: novelty, illuminating treatment of subject).
- In the USA, coded questionnaire forms are commonly used to quantify a study. In Finland there is usually not enough material for statistical validity (note! forms probe attitudes and prejudices, not facts)
- Case studies and qualitative research (used in social sciences and economics) are common in technology studies. Their method are not well known by engineering students.
Content of the lecture

1. Science is discussed for background and for understanding science-technology interface
2. The nature of technology is discussed
3. A top-down view of design and engineering
4. A draft for the "science of technology" is presented
5. Templates for technical science papers are presented, not as a norm, but to help to recognize a potential approach

A little bit of philosophy
- might not harm anybody ...

A top-down view of science and technology is exercised by the philosophers and sociologists of science (SSK - sociology of scientific knowledge). However, actual scientists usually learn their professional practices from their colleagues and in the work, bottom-up.

“For scientists, philosophy of science is about as useful as ornithology is for birds.”
probably first stated by Richard Feynman
Human activity – culture in large

- There are numerous fields of human activity (= culture in large)
  - Each field is related with knowledge, information, behavior patterns ...
  - Each field has internally set objectives and a tendency to evolve, find supporters and practicers and grow bigger
  - Fields have traditions for judging what is "relevant" and what is not
  - Science and technology are no more or less than human activity fields
  - They are different and distinct – but they do interact

Science and 21th. century science

- HOW MANY SCIENCES THERE ARE?
- Or: how many science classifications there are?
- Our model of "science" has been "formulated" in 1900 - 1950 but...
  - Scientific landscape has changed!
  - The Science Citation Index refers to > 8000 journals and > 200 disciplines (see OECD’s “Frascati manual” for an official view to classification)
  - The amount of R&D scientists varies form 5 to 20 million in world scale – depending on definition. Most R&D takes place outside the academic community. The statistics is based on education, and includes engineers.
  - The model of science is from physics. Its share of activity, according to publication statistics, is minor (data from different internet sources, in 2010)

But still, the most general principles of making science are universal!!
Aspects of science

General principles and philosophical issues of science are reviewed, to clarify science-technology interface.

"Knowledge is the mother of all virtue."
Muhammed ibn Ahmed Al-Biruni (973-1048)

Philosophy fundamentals in 15 seconds

- **The big issue**: what are the things and the world?
- Thus: the principal methodical problem is: *How can we find out about things and the world* !!
- We make some basic assumptions:
  - The world possesses enduring, real properties (forms, structures, movements, interactions), which do exist objectively - regardless of human comprehension or attention (realism)
  - Humans are capable of finding out about them, although it may be very difficult, because of our limited capacity (abandon skeptics)
  - **Science is a systematic (and proven) way to find out things***!!
  - It seems to be, that the nature is inexhaustible: the well of knowledge seems to be infinitely deep
“Definitions” 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)
     - Also raw data: a large and continuously growing and open supply of observations (data) just waiting to be analyzed
       (like data archives from space probes and physics research facilities, meteorological data, statistics and data banks of numerous other organizations)
   - Science is created and evaluated by the autonomically operating and self-regulating science community

The 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.
  - Instead of compact formulae he expressed ideas through verbal and logical proofs
- He employed thought experiments
- He used inclined plane to study movement (artificial 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 (natural) science and technology
The grand traditions of scientific thinking

1. Aristotelian:
   - Reasoning and human intellect as the main source of information
   - Aims for final explanations: "why"
   - Accepts different viewpoints; holism
   - E.g. social sciences, humanities; South Europe, catholic culture

2. Galilean:
   - Interaction between theories and observations
   - Aims for causal relations: "how"
   - Use of instruments for observations
   - Reductionism; ultimate goal reduction to basic physics
   - E.g. natural sciences, technology; North Europe, USA; protestant culture

The Galilean tradition established a close, autocatalytic interaction between science and technology, which has created the present, science-intensive technology

Dialogue between Aristotelian and Galilean thinking

- Scientists tend to apply Aristotelian reasoning, like "why this happens", "what is the reason for it", "what are the consequences"
  - During search of hypothesis
  - In narrative descriptions
  - In unofficial talk among professionals
  - To justify practical applications
  - In science popularization
- Galilean reasoning is the formal language of technical sciences
  - In hypothesis articulation and formulation
  - In justification of hypotheses
  - In formal criticism of dissertations
- There are individual differences and preferences in private thinking
Some common features of the scientific method

- Need of intuition
  - There is no "meta-theory", which tells how to invent the hypothesis or how to find a proof for it
- Gradual refinement of the problem and solution (Hans Reichenbach)
  - Discovery (pre-hypothesis, methodological fumbling)
  - Justification (clarification of hypothesis; proof or support of hypothesis)
- Verification and falsification (the latter highlighted by Karl Popper)
  - It is difficult to prove a hypothesis by positive evidence
  - Negative evidence works much more strongly against the hypothesis (the strict view that test by falsification is the only valid criteria, is disputed)
- Prediction (Hempel-Oppenheim principle)
  - A theory, which explains past phenomena or behavior, should also be able to predict future ones
  - Technical sciences predict properties of technical artifacts

Truth in science (and technology)

Truth theories are universal! But they are not prescriptive, nor exact. They do not work on the level of single papers, but rather on discipline and community level. Proposed theories:

Logical or mathematical integrity
  - Not really a criterion but a starting point; a ruthless falsifying test

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

Pragmatism
  - If a theory can be applied, it is valid (typical criteria in technology)

Coherence
  - What seems to fit in the big picture

Consensus
  - Common opinion among colleagues or community ("billion flies can't be wrong ...")
Aspects of technology

Technology is characterized conceptually, but also through its evolution.

“Anthropologists tell us that humans and their hominid predecessors have been conceiving, shaping and using artifacts from as far back as the early stone ages. We now call this activity technology.”

Subrata Dasgupta

Technology - one definition

- 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 consists of: a. artifacts, 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 artifacts
- Technology is not applied science - but applies scientific methods!
- 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
Major technology tracks

- Manufacturing and processing of bulk materials
  - Metallurgy, minerals, fertilizers, construction, petrochemistry, polymers, pulp and paper chemistry, semiconductors and nanomaterials; food processing
    *use of basic physics and chemistry; slow innovation*
- Manufacturing of assembled products
  - Buildings, ships, cars, machines, electronics, clothing ..
    *control theory, logistics, optimization; moderate innovation*
- Designing systems and mass produced artefacts
  - Defining new products; fitting products for production process
    *human cognitive process, ICT theories; fast innovation*
- Software manufacturing
  - Software for industrial use and for consumers
    *human cognitive process, ICT theories; very fast innovation*

Public and private in science and technology

INPUT

OUTPUT

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Dealing with private information

- Unlike in science, the critical knowledge in industry is confidential
- Critical knowledge is in organizations and in personal form
- Most technological knowledge is in tacit (unarticulated) form, it is difficult and inefficient to transfer
- Knowledge is also in artefacts: after a product launch, this information is exposed for reverse engineering
- Firms presently open their innovation processes and exchange information, because they focus on key competence
- Problems of private and restricted information (IPR, trade secrets) can be managed in research papers:
  - These problems are overcome by disclosing some information from scientific papers: like the source of information, or the exact application
  - Examples: company names in a method study are not told; product names or details of a usability study are not given.

Design and engineering

- the art of creating & applying technology

Design and engineering are the key processes in modern industry, because with consumer products and software the innovation rate is fastest. Since the age of renaissance masters, design has contained a creative element of drawing and sculpting

"..the artist has some of the scientist in him, and the engineer of both.."

Cyril Stanley Smith.
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 (1795) - still applied in engineering drawings.

Design, engineering and creativity

- **Design is creative activity, which creates new forms and new information about those forms**

  - In science, one major creative element is in formulating the research hypothesis
  - In technology, and in architecture, constructing a new artefact or introducing a new innovation is a major creative element
    - **Design science** explores conditions for this process; creativity itself appears difficult to approach
Engineering processes

- Since the latter part of the 20th. century, several process inventions have been made to make engineering more efficient
  - Systematic design process, "stage gate process"
  - Design refinement processes, QFD, requirement tracing
  - Project management process
  - Systems engineering process
  - Value engineering
  - Process assessment paradigm and assessment processes
  - Program and platform approaches
  - Iterative and agile processes

- Despite the process revolution, design and engineering have preserved their creative nature

How engineers study and justify their creations (evolution of methods)
The quest for science of technology

Is there a science of technology? Should there be?

"Knowledge is power"
Francis Bacon (1561-1626)

- "Sciences of the artificial " (H. A. Simon 1981 Nobel prize in economy):
  - There is no unified science of technology
  - There should be!
  - It should integrate design science with the science explaining artefacts
  - (Also Karl Popper considered, that the artificial has a special character)
- Following Simon´s reasoning, we can describe the objective of the science of technology:
  * To describe, explain and predict properties and behaviour of man-made objects and materials
  * To analyse, explain and model engineering, manufacturing and production processes
  * To address interactions associated with manufacturing, adoption and utilisation of technical artefacts: from the viewpoint of a person, society, organisation, business, community and environment
**Choice of research approach:**

- **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**
  - Usability research (cognitive psychology, experimental psychology, linguistics, ergonomics)
  - Management and organization science (sociology, psychology)
  - Innovation research (sociology, economics, psychology, ergonomics)
  - Design science, programming (cognitive psychology, mathematics, linguistics)

**Main categories of science 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
   - Examples 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...)

*Two important cases...*
Innovation research (cat 3)

Innovation = large scale implementation and utilization of new technological inventions and applications

- **Innovation research** is an interdisciplinary science which combines technology, social sciences, economy and industrial management.
- How innovations emerge? How they propagate? Why they fail?
- Focus is shifting from sociology and political science towards industrial management, and towards business, design and knowledge issues
- Contemporary innovation related topics and buzzwords:
  - Competition advantage, user centered design, user innovation
  - Development and management of knowledge and competence
  - Innovation strategy, innovation management, open innovation ...
- Innovations may be studied by statistical methods (penetration of use, diffusion rates)
- Also applicable: qualitative research and case study research.

Constructive research (cat 2)

- **The idea is to create some artificial structure which provides information for your research problem.** You may try to support or falsify your research hypothesis, or to collect data for a theory.
- Constructive research is used on many branches: social sciences, psychology, organizations research, management science...
- In technology, constructive research is a common high-level approach
- The construct serves only as an instrument. It still remains to validate the objective of the construction, and to generalize its lessons.
  - You may want to find out about the constructed object, about the construction process, or about coping with the object
  - Because your construction process is more or less artificial, you are conducting a laboratory experiment, which may distort the situation.
  - A construction is one-of-a-kind effort. It is often difficult to generalize. Constructive research comes close to qualitative research and case study research. You should be aware of capabilities, limitations and methods of qualitative research.
Templates for technology related research

This is not an exhaustive list or categorisation, but it may be useful help for recognizing the mode or approach of study

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 acts not in open space, but 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 issues; creativity; group dynamics; design culture
  - Managing the design process; managing requirements, technologies, costs, manufacturability; other constraints.
  - Usability and product life cycle issues
- Industrial management approach
  - Technology-business interactions; strategy issues
  - Networking issues; technology-market interface
  - Managing engineers, processes, quality, competence, knowledge
- Manufacturing approach
  - Processes, machinery
  - Product-process interaction
  - Logistics, material and energy flows; networking
  - Design-manufacturing interface

Studying use, adoption, impacts

- End user and consumer issues
  - Usability studies, ergonomics, 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
To conclude ...

* Create a curious attitude!
  What do you want to know? Why it is important?
* Choose your viewpoint!
  Is it: nature of things? making of things? consequences of things?
* Secure your background! Read! Ask! Discuss! Read more!
  Remember to make notes, and start collecting references
* Write boldly!
  Writing reveals what you do not know, and stimulates creativity
* Follow your star!
  You may explore sideways, your shining star prevents you getting lost
* Finish your work!
  Stop - or cut it - it is not the theory of the universe, just your thesis!

Supplementary reading

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


12. Rosenberg, N. 1976. Perspectives on Technology. Cambridge University Press [a versatile analysis of technology; industrial cases from USA]

