How to Get a Ph.D.: Methods and Practical Hints

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Abstract: This paper includes an introduction to research methodology for doctoral students in engineering sciences. A doctor must be able to discover new knowledge independently, and this is shown by original conference and journal papers. The research methods are used within analytical and systems approaches by combining analysis and synthesis. There is no straightforward method to find solutions to research problems, but creativity can be encouraged in different ways.

Keywords – research methodology, doctoral studies, engineering, analytical approach, systems approach

I. INTRODUCTION

Doctoral studies in engineering sciences take a minimum 3–4 years of full-time work after the master of science degree, including possible courses and exams. The studies may take even longer if students are working only part time for their doctoral theses. Thus good advices are needed so that all the available working hours are used efficiently.

There are only a few recent books [1]–[3] available to support doctoral studies in physical sciences and engineering. There are many similar books for social sciences [4]–[6], but research methods are somewhat different although there is some overlap. Many books about research methods are actually writing instructions, but research is much more than that. Philosophy of science, also called theory of science, studies fundamentals of science with a somewhat more abstract approach [7], [8].

Any research starts from the definition of a question or a research problem, and the goal is to find an answer or a solution to it. This is the essence of research. We can divide research into two basic parts, namely discovery and verification [8, pp. 857–858]. Therefore, a research project typically includes the following phases in a highly iterative way [1]–[3], [9]:

1. Definition of the problem, also called the set of objectives.
2. Initial collection of data including a literature review and tentative experiments.
3. Proposal of a tentative solution, also called hypothesis or goal.
4. Refining and verification of the solution by using the hypothetico-deductive method.
5. Publishing the refined and verified solution in a scientific paper. Research is not ready if the results are not published.

The three major methodological approaches in research are analytical, systems, and actors approach (Fig. 1) [5, pp. 47–79]. In the analytical or reductive approach we assume that a whole is the sum of its parts [10, p. 31]. In the systems or holistic approach we admit that a whole differs from the sum of its parts because of interactions between the parts [10, p. 91], [11, p. 55]. Most books present only the analytical approach, but there are some important books on the systems approach [9], [11], [12].

The actors approach is a generalized version of the systems approach where the actor, a conscious human being, is an essential part of the system. Observations become subjective in the actors approach.

Different research methods used within the methodological approaches [5, pp. 1–20] can be divided into nomothetic, constructive, and idiographic research (Fig. 1) [13, p. 547], [14]. In nomothetic research the aim is to find general causal laws to
describe phenomena. Theories are usually axiomatic systems or sets of theoretical models, but they can be also statistical [7, pp. 59, 68–105]. In constructive research the solution of the problem is not only shown to exist but it is constructed in the form of a prototype. In social sciences a social situation may be constructed and studied. In idiographic research we are interested in nonrecurring events such as in history and we want to explain them.

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Figure 1. Methodological approaches and research methods

Each method can be used in different methodological approaches, but for example nomothetic research is usually used within the analytical approach. In this paper we exclude the actors approach [5, pp. 157–211] and idiographic research [13, p. 547], [14], which are important in engineering sciences related to social sciences, for example in industrial management.

The rest of the paper is organized as follows. In Section II we provide an overview of doctoral studies in engineering. In Section III we summarize the preparation of a literature review. In Sections IV and V we cover the analytical and systems approaches, and in Section VI the basics of writing a scientific paper are given. Section VII concludes our paper. We have also collected a brief bibliography for a doctoral student at the end of this paper after the list of references.

II. OVERVIEW OF DOCTORAL STUDIES

The official requirements of doctoral or postgraduate studies after the master of science degree include specialized studies and the doctoral thesis. Sometimes the term “graduate studies” is used and it refers to studies after the bachelor of science degree. The specialized studies may include courses and exams equivalent to one academic year of full-time work.

Normally a doctoral student must submit a proposal about the postgraduate studies [4, pp. 72–105], [15]. The rules vary in Europe from country to country, but they are being unified in a process called Bologna process.

The general requirements of a doctoral thesis are summarized in [4, p. 11]. The student must show ability to discover independently new scientific knowledge with an appropriate methodology. The student must prepare a doctoral thesis including a literature review, the verified results and related discussion, and defend it successfully in a public defense. Several scientific papers which deal with an integral set of problems are usually appreciated.

The student has a supervisor and a few advisors. The thesis supervisor is the official representative of the university, usually a professor or an adjunct professor, who gives general guidance and checks that the rules of the university are followed. The thesis advisor is usually a representative of the workplace and gives day-to-day guidance. The supervisor and the advisor read the thesis before the pre-examination made by independent reviewers. Especially if the student prepares the thesis at a university, the supervisor and the advisor can be the same person.

The advisor does not give any ready-made solutions but rather ways of thinking and encourages the student to use the available infrastructure on the student’s own initiative. The development of research culture depends heavily on advisors. The student does the detailed planning in the form of a thesis proposal [15], including for example a detailed time schedule with intermediate steps, carry out the actual research, write the manuscript of the thesis, and follow the given recommendations from the supervisor and advisors. When the manuscript is ready, it is examined by at least two independent reviewers. Finally in a public defense the student defends the thesis and the
university gives the degree by using the recommendations of the opponents in the public defense.

In research our goal is to discover new knowledge [16, pp. 7–8]. Understanding is promoted by finding regularities and dynamical explanations [17]. In basic research no specific application is in mind, but in applied research ideas are put into an operational form [16, pp. 7–8]. Development is systematic use of existing knowledge. Research and development are closely related since in constructive research a prototype is developed to demonstrate new ideas. If a project does not produce scientific publications, it is not considered to be research. Working prototypes often include tacit or silent knowledge that is not included in any documents.

Natural sciences, also called sciences, and technology are clearly different although they use similar approaches and methods. Science is “organized knowledge of the physical or material world gained through observation and experimentation” [18]. Technology is the scientific study and use of for example engineering and industrial arts. Technology deals with the ways we provide ourselves with the material objects of our civilization [18].

In natural sciences the objects of study are objects in nature, but in engineering sciences they are products, services, and methods, not found in nature. The term “applied science” for engineering is a misnomer. Engineering science is a science of its own although it uses similar methods and the results of mathematics and physical sciences. Engineering must follow the natural laws and rely on the basic resources in nature such as materials and energy.

Research is a challenging learning process that needs enthusiasm. Some knowledge on learning is useful. Usually students learn by using the bottom-up approach by starting from something familiar and concrete and proceed towards unknown and abstract [19]: “He who would climb the ladder must begin at the bottom”. Students prefer to study simple examples from which they generalize the results.

Professors usually have the top-down approach. They start from theoretical abstract principles and derive from them some more concrete results. They already have the whole picture and they find it natural to teach it in this way. They have forgotten how they learned the topic. The students on the other hand find the top-down approach difficult. It is something like teaching grammar to a child that does not even know the words. A child learns the first language without knowing anything about the grammar, simply by imitating what adults are saying and first learning some sounds, words, and example sentences. Later at school knowledge of the grammar supports the learning of the language. In practice, bottom-up and top-down approaches should be combined to make learning efficient and complete.

Knowledge of history is essential in learning.

History. The first modern university is the University of Bologna that was founded in 1088. The university system took its model from Plato’s Academy that was closed in 529. The first university of technology was founded in Budapest in 1782. More recently the Bologna process was started in 1999 to unify the university degrees.

The word “doctor” comes from the Latin word doctor, which refers to a teacher [20]. The word was used for a holder of the highest degree in university first time in 1375. The abbreviation Ph.D. is an abbreviation of the Latin words philosophiae doctor or “teacher of philosophy”. Science was originally called natural philosophy until about 1737 [21, p. 286]. The word science comes from the Latin word scientia or “knowledge” [20]. The word research comes from the old French word recercher or “seek out, search closely”. The word technology is from the Greek word tekhnologia “systematic treatment of an art, craft, or technique”. The word engineer comes from the Latin word ingenium “inborn qualities, talent”.

III. LITERATURE REVIEWS: EXISTING KNOWLEDGE FROM DATABASES

Scientific knowledge is freely available in publications, normally through libraries but nowadays often through the Internet. A literature review is a written well-organized
summary of the current technology or the state of the art with a clearly defined focus. A literature review should be the second chapter in your thesis [15]. A brief review is also needed in every original paper in its introduction. A review in an original paper and a doctoral thesis is written to experts in the field. A review may include historical notes as for example in [22]. A document without any review of literature is not a scientific document.

As a doctor you must know the existing literature [4, pp. 11, 93], [15]. In this way you have a large picture of the subject, you can show the originality or novelty of your work, you have the list of references for your thesis [4, p. 93], and you can in some cases find ideas for new research [16, p. 29]. Most ideas come, however, through discussions.

According to the Computerized Engineering Index (Compendex) database almost 2000 papers are published each day in engineering. Therefore we must be very selective what we read. Usually it is best to concentrate on landmark books and papers at least initially. Experienced researchers may find also other papers useful.

Publishers are either nonprofit scientific societies, for example Association for Computing Machinery (ACM), Institute of Electrical and Electronics Engineers (IEEE), and International Society for Optical Engineering (SPIE), or commercial publishers, for example IEEE Press, McGraw-Hill, Prentice-Hall, and John Wiley & Sons. Publications can be divided into books, periodicals, conference proceedings, and technical reports.

Books include established knowledge in reference books, monographs, textbooks, and popular trade books [23, pp. 172–175]. The most important reference books are encyclopedias from which you should start whenever you are in a new field. A very useful encyclopedia is Wikipedia, but it does not have a peer review process unlike many printed encyclopedias. A good collection of encyclopedias is Answers.

A monograph corresponds to an extended review paper and both are written for an expert in the field. A textbook corresponds to an extended tutorial paper, which is a review paper written for students and beginners. Books can be either authored or edited. In general, authored books tend to have a higher quality because it is easier to unify the work of only one to three authors. Books are written by experts in the field but one problem is that they usually do not have any review process. Only the book proposal is peer reviewed. The quality must be estimated from the reputation the publisher and the authors, and from the contents.

Scientific periodicals are divided into journals and magazines. Archive journals include review papers and original papers. The latter include full or regular papers and short papers called letters or correspondence. A full paper is “a well-rounded treatment of a problem area” [24]. Letters include “comments on published papers, corrections, and open problems as well as new high quality technical contributions, primarily representing enhancements of a previous paper” [25]. Magazines are less formal than journals and the papers are often of tutorial type and they do not include many equations.

Conference proceedings are usually records of original papers, but some invited papers may be in the form of review papers. A small conference is often called a symposium but otherwise it does not differ from a conference. Workshops are less formal scientific meetings and sometimes only the copies of the slides are distributed to the audience. Even smaller and informal meetings are called seminars. The most mature papers are presented in conferences, symposia, and journals.

Scientific knowledge is collected into bibliographies, abstract and citation databases, and electronic libraries. A major part of scientific databases are journal, magazine, and conference papers. Bibliographies include lists of references that are arranged according to the subject. An author index may also be included, and the references may include annotations. An annotated bibliography is the first step towards a review paper. Bibliographies can be found from textbooks, review and tutorial papers, and anthologies of original papers, for example those published by IEEE Press. Short but important bibliographies are also in the introductions of
original papers. In some databases you can make a search by using the document type “bibliography”. Some experts in the field publish bibliographies on their home pages.

The largest collections of databases in engineering are Engineering Village, Web of Science, and Scopus. Engineering Village includes two large databases, Compendex and Information Services in Physics, Electrotechnology, Computers and Control (Inspec), having much overlap. They are abstract databases that do not include any citations. Citation databases include, in addition to abstracts, also lists of references. When an earlier book or paper is mentioned in a list of references, the earlier reference is said to have a citation. The citation links are a very efficient way of finding the newest knowledge. Web of Science includes Science Citation Index Expanded but also corresponding citation indices for social sciences, and arts and humanities. In Web of Science conference papers are in a separate Conference Proceedings Citation Index.

Scopus is also an abstract and citation database. It is the largest of the present scientific databases. It includes 37.6 million records (2008) of which 6.1 million records are in engineering. For example Compendex includes 11.2 million records and Inspec includes 10.4 million records. Engineering Village is therefore very useful for engineers although it is lacking citations. The size of scientific databases increases exponentially. The number of records per year is doubled every 10–15 years depending on the field.

Scientific societies collect their own papers as portable document format (pdf) documents in electronic libraries, which can be subscribed. Examples include IEEE Xplore Digital Library, ACM Digital Library, and SPIE Digital Library. One of the largest electronic libraries is IEEE Xplore that includes 2.0 million records (2008). Electronic libraries are also abstract and citation databases, but the citations are available only for the newest papers. Google Scholar is a general tool that can be used for searches of scientific papers on the Internet including electronic libraries and it includes also citations. Google Scholar is using the PageRank algorithm [26] for ordering the references and therefore usually the most relevant references are on the top of the list, but many of them are not scientific. Google Scholar makes searches from the whole document, not only from the title, abstract, and keywords as in ordinary databases. This is useful especially if the keywords are rarely used.

Books are often published by commercial publishers. They publish lists of their own books but usually only the table of contents and perhaps some sample pages are available. There are electronic libraries for old books and journal papers, especially for those whose copyright has expired. Those documents are in the public domain for anybody to use, but still a reference and quotation marks in verbatim citations are needed when you use the material. The most important databases for old books and journal papers seem to be Open Library for books and Journal Storage (JSTOR) for journal papers. In Open Library there are links to other similar databases, for example Google Book Search, and therefore Open Library is a good starting point. In general the full contents of new books are not included or only an extract is available because of copyright limitations.

Some bookstores also publish new books for limited browsing to make buying decisions easier. You can make searches within the books and browse a few pages if you are registered. Usually registration is free of charge. One large bookstore that offers limited browsing of new books is Amazon. You can search for keywords in the full text of many books. Amazon includes also references and citations for new books. Libraries keep a record of their own books. You can find also books and their citations with Google Scholar.

Review and tutorial papers are available in the databases among the original papers. They can be found by using the document type “review”. You can use also keywords “history”, “overview”, “survey”, and “tutorial”. Review papers can be found from review journals (for example Proceedings of the IEEE) and special issues of ordinary journals. Many tutorials are available in magazines. Doctoral theses should include good reviews of literature.
Standards are special normative technical reports, which are good sources of state-of-the-art information, but sometimes the decisions made in the standards are political. Standards are prepared and sold by standardization organizations such as International Electrotechnical Commission (IEC), IEEE, International Organization for Standardization (ISO), and International Telecommunication Union (ITU). The newest information is available only for active members of the standardization groups. Usually the strongest members come from large industrial companies. Some standards are freely available on the Internet, and IEEE standards are available in IEEE Xplore.

Patents are accepted invention reports that differ from scientific papers in the sense that their aim is to limit the use of knowledge in commercial products although the patents are public. Their writing style is often ambiguous to make their scope as wide as possible. They may include information that is nowhere else. They can be found from World Wide Web (WWW) pages of patent offices or for example from Free Patents Online. Doctoral theses are technical reports published by universities, nowadays often on the Internet.

When using literature it is best to proceed from general information, for example in encyclopedias, textbooks, and reviews, to more specific. The newest information is usually in conference papers, but they are not always reliable. It is important to learn the terminology, also in your native language. National standardization organizations publish their own vocabularies and translations of international vocabularies. Landmark or seminar books and papers are most useful. You can find them through bibliographies. The relevant questions for a literature review are: what is the state of the art and what development lead to it. You own research must then go beyond the state of the art or, equivalently, beyond the prior art.

The literature review is organized according to the topics, not according to the historical progress, which is usually bottom-up and the papers may sometimes be disconnected because of independent parallel research. A hierarchical top-down classification or taxonomy is useful to organize the material. In addition to the literature review, separate historical notes may be given. An excellent example of a review paper is [22].

History. Books have been available since the antique, but the first books were printed in 1455 by Gutenberg [23, pp. 4–5]. A good summary of the history of scientific journals is in [27]. The first scientific journal was Transactions of the Royal Society of London in 1665, published just after the Royal Society was founded in 1660. The Royal Society is the oldest scientific society that still exists. One of the first regular international scientific conferences in physical sciences was Solvay conference that was organized in 1911. The conferences in engineering have been organized by large scientific societies. For example ACM was founded in 1947, SPIE in 1955, and IEEE in 1963 by merging two earlier societies that had been founded in 1884 and 1912.

The first abstract journals were published soon after the first archive journals [28, p. 152]. The first true citation index is from the year 1860 although citation analysis had been made even earlier in 1743 [29]. The oldest abstract journal in engineering is Engineering Index (1884), but Inspec started soon after that (1898) with the title Science Abstracts.

The large abstract databases in the Engineering Village originally started from the year 1969. The Science Citation Index was originally produced in 1960. The Web of Science typically starts from the year 1986, but this depends on the agreement that the library has made. There is material from 1900 onwards. Electronic libraries became available in about 1996. For example IEEE Xplore electronic library originally covered years 1988 upwards. Databases are still rather new and therefore they are not yet complete, especially regarding the old references and citations. Pure abstract databases may be more comprehensive in engineering than the citation databases.

Normally journals must be subscribed. Open Access (AO) journals are free to everyone since their authors pay a publishing fee. OA journals have been
published since 1990. Electronic publishing became popular after the WWW was made commercial in 1994.

IV. RESEARCH METHODS: ANALYTICAL APPROACH

Analytical approach has been the reason for the success of the western culture [10, p. 34] to such an extent that the approach is often called the scientific approach. It is based on two principles: deductive structure and verification of theories through experiments. Deductive structure guarantees the coherence or unity of the theory. Verification though observations and experiments show that theories correspond to the reality.

Scientific method is “a method of research, in which a problem is identified, relevant data are gathered, a hypothesis is formulated, and the hypothesis is empirically tested” [18]. A hypothesis is a provisional theory suggested as a solution to the problem. It may be either a causal relationship or correlation between random variables. Correlation does not imply causality because correlation can be a result of a common cause. Therefore correlation is a weaker explanation than causality.

In science three basic types of reasoning or inference are used. They are deduction, induction, and abduction. Deduction is a type of reasoning which has the following property: if the premises are true, the conclusions must be true [8, p. 194]. This means that deduction preserves the truth. In mathematics deduction is widely used and especially in engineering is often called analysis [9, p. 110]. Deduction is sometimes loosely defined as proceeding from general to particular. The conclusions are implied by the premises. There is no new information in the conclusions that would not be in the premises, i.e., the premises form a complete although implicit summary of the conclusions.

The concept of induction may refer to scientific induction or mathematical induction. Scientific induction, sometimes called Bacon’s induction, is incomplete: it is reasoning where the conclusion, though supported by the premises, does not follow from them necessarily [8, p. 432]. In scientific induction the truth is not necessarily preserved, which forms a problem called Hume’s problem of induction. Scientific reasoning from observations to theories is often held to be a paradigm of inductive reasoning, but more appropriately we should use the term formation of hypotheses. The conclusions may include more information than the premises. Often induction is loosely defined as proceeding from particular to general; we use an extrapolation in space and time. Induction is a form of synthesis [9, p. 110].

Mathematical induction, sometimes called Fermat’s induction, is a special case of complete induction that is used in mathematical proofs [30, p. 25]. Complete induction is induction where all the special cases of the generalization are enumerated. It is actually a form of deduction and therefore must be clearly differentiated from scientific induction.

Abduction is “inference to the best explanation” [8, p. 1], i.e., induction that has been somehow “optimized”. In strong inference we approximate abduction: we use several competing hypotheses and select the best one [31]. Reasoning may be also statistical, which leads us to the inductive-statistical model of explanation [7, p. 59].

An essential part of any research is formation of concepts and theories [32], [30]. A semiotic triangle includes three aspects or descriptions of reality: an object, a term, and a concept [8, p. 863–864]. The term is a word that is used as a symbol for the object. The concept is the idea behind the object “formed by mentally combining all its characteristics” [18] and summarized in a definition. Scientific terms are defined in vocabularies, such as [33], prepared by standardization organizations.

Definitions are divided into ostensive, dictionary, and stipulative definitions [8, pp. 194–195]. Ostensive definitions are pseudodefinitions where elementary or primitive terms are explained by examples to avoid endless loops of definitions. Dictionary definitions try to describe how the terms are normally understood. Stipulative definitions are definitions by agreement. They are widely used in science: we give a more specific meaning
for a term that we can find in a dictionary or we invent completely new terms. A good definition is such that it names a wider class to which something belongs and distinguishing properties. For example “a triangle is a closed plane figure [a wider class] having three angles and three sides [distinguishing properties]”. In this way we obtain a hierarchy of concepts and show their relationships.

Scientific theories only describe, i.e., answer to the question “how”, but they do not strictly speaking explain, i.e., answer to the question “why”, although the word explanation is often loosely used for scientific theories [13, pp. 26–28]. Theories may be deterministic and deductive such as the theory of relativity, or probabilistic or stochastic such as the quantum mechanics. Scientific theories have the following properties: agreement with reality, coherence, generality, and fertility [34, p. 109]. In addition to theories and prototypes, engineers use also written descriptions, drawings, and tables.

Theories are divided into axiomatic systems and sets of theoretical models [7, pp. 68–105], [8, pp. 74, 617, 914], see Fig. 2. Axiomatic systems are an ideal form of theory where theorems are conclusions that are derived deductively from primitive symbols, definitions, and axioms. The axioms are premises or assumptions. Axiomatic systems are either Hilbertian or hypothetico-deductive systems [32, pp. 205–208]. In Hilbertian axiomatic systems, which are used in mathematics and other formal sciences, no interpretations are made what the objects in the system mean in reality. Tentative theorems are called hypotheses or more often conjectures that are proved by deduction. A good example of Hilbertian axiomatic systems is Euclidean geometry. A famous conjecture or unproved theorem is Goldbach’s conjecture [8, p. 348]

In empirical sciences such as physical and engineering sciences hypothetico-deductive systems are used. The axioms are hypotheses that are interpreted and verified indirectly by using the hypothetico-deductive method by comparing the claims in the theorems with reality. Strictly speaking verification is not possible because it always includes inductive reasoning [7, pp. 112–116]. Only falsification is possible, but even this claim has been criticized [7, p. 134]. The interpretations where the theories become materialized are called models [32, p. 205]. A good example on hypothetico-deductive systems is Newtonian mechanics where the axioms are the three laws of motion and the universal law of gravitation.

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**Figure 2. Comparison of theories**

In theories that are based on sets of theoretical models the results are derived by deduction from the primitive terms, definitions, and assumptions of the model (Fig. 2). The structure is similar to that of an axiomatic system. Theoretical models are common in empirical sciences. Examples include ideal gas and Bohr’s model of the atom. Theoretical models are most probably only an approximation of the reality.

It is emphasized that the term “hypothesis” is used in a different way in formal and empirical sciences. In formal sciences the hypothesis is a tentative conclusion called the conjecture, to be proved by deduction from the axioms, in empirical sciences the hypotheses are the premises called the axioms or theoretical models, which are verified indirectly by using the hypothetico-deductive method.

More generally, models can be classified by structure into 1) physical models, for example a map in the form of a globe, 2) theoretical models, which may be conceptual or mathematical, and 3) analog models where often electronic circuits are used as models [35, p. 126]. Theoretical models may be conceptual, for example block diagrams or flow charts, or mathematical, represented by mathematical and logical symbols.
Mathematical models can be solved by analytical methods, numerical deterministic methods, and random or stochastic sampling [35, pp. 126–127]. By “solving” we mean finding of the optimum or the worst case. A summary of various solving methods is presented in [36]. Analytical methods are desirable because an exact answer is derived by deduction, but this method is useful in rather simple cases that are mathematically tractable. Tractable systems are usually linear and if they are stochastic, they are usually Gaussian. In numerical deterministic methods some kind of iterative procedures are used for example with the Newton method. A problem is that there may be local minima and we must complement the method by an exhaustive search with a coarse resolution. In engineering we sometimes use the terms acquisition for the exhaustive search and tracking for the iterative search. In random sampling we use Monte Carlo simulations, i.e., we repeat a stochastic experiment many times and average out the performance. The model is in fact not “solved”, but approximate optimization can be done by exhaustive search by varying the parameters of the model, usually one at a time. In semi-analytical methods we combine analytical and simulation methods.

Deductive explanations cover a wide range of explanations whose subsets are deterministic and causal explanations [13, pp. 73–78, 278–293], [37, p. 15]. All causal theories are deterministic, but not all deterministic theories are causal. For example Boyle’s law is deterministic but does not tell about a causal relationship although there is some causality behind the law, as can be shown by a more detailed theory.

A whole can be broken down in two different ways, either into parts or properties (Fig. 3). If the whole is a concrete whole, we sometimes replace the term “properties” by observations. If the whole is an abstract whole, i.e., the premises of a theory, we replace the term “properties” by conclusions. When a whole is broken down into either parts or properties, we call it analysis. When a whole is put together from parts and required properties, we call it synthesis.

Figure 3. A whole and its parts and properties

All deterministic systems are causal. Causality can be divided into forwards causality and upwards causality [8, pp. 77, 131–133]. Forwards causality refers to Aristotle’s efficient cause, i.e., causality in time: a cause always precedes an effect. Forwards causality can expressed with deduction [37, p. 15]. The opposite of the efficient cause is a final cause or purpose. Upwards causality refers to Aristotle’s material cause, also called part-whole causality: a whole is caused by its parts. The opposite is the downwards causality or Aristotle’s formal cause, also called whole-part causality: a whole has some effect on the parts. Downwards causality is sometimes offered as an explanation for free will [8, p. 133]. In the analytical approach we reject backwards and downwards causality, which would be conflicting with the idea of reduction. At the same time this is a major weakness of the analytical approach. In Fig. 3 causality proceeds from the parts to the whole, referring to the upwards causality, and from the whole to the properties, referring to the forwards causality.

Emergence refers to “occurrence of properties at ‘higher’ levels of organization which are not predictable from the properties found at ‘lower’ levels” [13, pp. 366–380]. Such properties are not additive such as the mass of an object [8, pp. 239–240]. A simple example of emergence is temperature of gas. Single molecules do not have temperature, which is a property of a large number of molecules. We can extend the concept of emergence to forwards causality. This need can be more clearly seen in evolution theory where evolution has proceeded forwards in time and upwards in hierarchy. Thus emergence can be defined as appearance of properties that cannot be explained by causal relations, neither upwards nor forwards causality.
The analytical approach cannot explain emergent phenomena that are caused by complicated interactions between parts [11, p. 55], and therefore we need systems approach. We should understand that the whole is not only a set of its parts but also of their relationships.

We define reduction as a search for causes and therefore it proceeds in the opposite direction to causality. The cause of properties is the whole and the cause of the whole is its parts (Fig. 3). The term reduction is used in three meanings: methodological, epistemological, and ontological reduction [34, pp. 230–233], [8, pp. 793–794]. Methodological reduction refers to our analytical approach where we study the behavior of complex wholes by analyzing their parts and properties, i.e., we use ontological and epistemological reduction.

In the epistemological reduction we order theories so that the most general theory is on the top and the most primitive theory on the bottom just above observations [8, p. 668] (Fig. 4). The order is a matter of opinion, see for example [38, pp. 58, 113]. Thus sometimes the observations are on the top and the most general theory on the bottom.

In epistemological reduction we claim that theories at any level of analysis can be reduced to more general theories at a higher level (Fig. 4) [7, pp. 68–105]. A good example is the reduction of the Newtonian mechanics [reduced theory] to the theory of relativity by Einstein [reducing theory].

When the observations are reduced to a theory, we can call it induction or more generally formation of theories and it corresponds to synthesis. The whole corresponds to the theory and the properties correspond to the observations (Fig. 3). The opposite of epistemological reduction is deduction, which corresponds to analysis. Science proceeds upwards from the observations through primitive theories to more general theories just because this is the way how human beings most naturally learn. In an abstract whole we proceed backwards from the better known and specific, i.e., observations, to the less known and general, i.e., theories (Fig. 3). Since theories are usually drawn hierarchically, we proceed upwards from observations to theories (Fig. 4).

In ontological reduction we claim that reality consists only of simplest components such as atoms organized in particular ways. We use a hierarchy where the concrete whole, which is specific, is on the top and its parts, which are general, are on the bottom (Fig. 3). In a concrete whole, if it exists, we proceed downwards from a whole, which is better known to us, to the parts, which are less known to us such as in particle physics. In engineering the whole does not initially exist, and therefore we start from the bottom just like evolution has proceeded from the bottom. In engineering we proceed from simple parts such as transistors and we proceed to wholes such as integrated circuits, not vice versa. In engineering the top-down approach is called “reverse engineering”, and it can be used to learn how an existing system works.

Sciences form a hierarchy such as history, economics, sociology, psychology, biology, chemistry, and physics [12, p. 52]. Often it is claimed that physics is the most fundamental science, but so far reduction has been shown only for chemistry that has been reduced to physics [21, p. 556]. Although sciences are theories, they are usually presented hierarchically following the order in ontological reduction so that physics is on the bottom.

Some explanations are inductive-statistical [7, p. 59] as an opposite of deductive-nomological explanations [7, p. 28], which we have described so far. Inductive-statistical explanations employ statistical generalizations instead of deterministic laws. Statistical theories are
neither deductive nor causal [13, pp. 22, 77].

Empirical research is divided into discovery and verification [8, pp. 851, 857–858]. In the philosophy of science the main emphasis is in the problem of verification. In *discovery* a hypothesis is formulated from the observations. It may be refined when new data become available. The discovery phase cannot be easily described, but some books [39] give good historical examples. They can be classified as follows [39, p. 6]: improved measuring instruments, understanding of patterns in data, hypothetico-deductive method, clarification of discrepancies, deduction from premises, imagination, intuition, and serendipity or luck. The research problem must be well defined.

Creativity exists on the edge of order and chaos; we use methodicalness but also flexibility, usually alternately. Pure order is not creative: we just do the same what has been done many times before. If we are too flexible, we most probably produce just more chaos. To fasten the creative process we must have something on which we can build, i.e., some order and some chaos. Often creative moments are those when we have some quiet time without too much to do or we are in a new environment such as at a conference. Active doing such as writing may help creativity.

There are no deductive ways from problems to hypotheses, we need an abductive approach. We can only try to encourage our creativity by selecting our environment and by using analogies, symmetries, opposites, and extremes. Some groups are especially creative. Such groups have talented people with different backgrounds, and they have a freedom to think and criticize impersonally the weaknesses in the used methodology. Ordinary people often think that criticism is bad, but in fact criticism is the only way to improve the output of a research group.

*Analogies* are useful for finding hypotheses but may sometimes refer to superficial similarities [11, pp. 84–85]. If the causes are different, but the laws are formally identical, such a correspondence is called a *homology*.

The traditional methods of discovery include divide and conquer and iterative improvement [40, p. 96]. Divide and conquer uses the methodological reduction where a large problem is divided into simpler subproblems which are solved and the solutions are finally combined. Experiments and induction are used and therefore sometimes the method is called inductive-experimental [38, p. 55] or rather experimental-inductive. In iterative improvement we guess a solution and then we try to improve it. Most solution methods include iterative methods because the problem and hypotheses are initially not very clear and it is even difficult to understand the literature. Understanding needs knowledge of terminology and some experience. The latter is gained by own experiments and discussions with more experienced researchers. Seminars are good places to exchange information.

![Figure 5. Hypothetico-deductive method](image)

**Figure 5. Hypothetico-deductive method**

Hypotheses are verified by using the hypothetico-deductive method [7, p. 69]. In engineering we initially do not have any whole but only the user needs, which are converted to a set of performance metrics or criteria and the corresponding performance requirements. Therefore the hypothetico-deductive method must be modified (compare Fig. 5 to Fig. 3): the whole is replaced by the requirements. A research problem is often an optimization problem where the optimum or worst case is found by using an optimization criterion.

The theoretical system model and the prototype are verified against the requirements and the prototype is finally validated in the field tests [33, p. 31]. Validation is in fact verification of the requirements. It may happen that the requirements do not fully describe the user needs.

**History.** The history of the analytical approach is presented in [38]. The word
nomological comes from the Greek word nomos “law” and logos “word, doctrine, reason” [20]. The word nomothetic is derived from the Greek word nomothetēs “lawgiver” and the word idiographic is from idios “one’s own, personal, private” and graphein “to write, to draw”. 

The word analysis comes from the Greek word analyein “unloose”, and the word synthesis from syntithenai “put together, combine” [20]. The word deduction comes from the Latin word deducere “lead down, derive”, the word induction from inducere “lead into”, and the word reduction from reducere or “to bring back”. 

The first researcher known by name is Thales who noticed that there is some regularity in nature; it is not completely capricious [12, pp. 3, 25]. Thales was also one of the first to use deduction. Leucippus discovered atomism and causality. Later Socrates developed the dialectic method. His student Plato realized that we observe only a shadow of reality with our senses. His cave example is famous. Plato’s student Aristotle used induction and deduction, the axiomatic system, and classification. He defined four causes, including the efficient, final, material, and formal cause. 

The Greeks invented abstraction or idealization and generalization, but they also committed two serious errors: they considered deduction as the only respectable means to attain knowledge and they thought that axioms are “absolute truths” [41]. The errors eventually led to a dead end. 

Occam used the principle of parsimony or Occam’s razor (1327): we should select the simplest theory if there are several theories that predict the observations. The modern analytical approach using experiments was developed in the 1600s by several people including Galileo, F. Bacon, Descartes, and Newton, based on the earlier work by Copernicus and Kepler. This was the start of the scientific revolution. Usually most of the credit is given to Galileo, but in fact the experimental method was used 600 years earlier by Alhazen in Arabia. Experiments were also emphasized by F. Bacon although he did not do experiments himself. Galileo used methodological reduction, but Descartes described it in detail [10, p. 31], [12, p. 46]. The hypothetico-deductive method was clearly formulated by Boyle in the middle of 1600s [30, p. 128]. 

The problems of induction and causality were discussed by Hume (1739). Whewell stressed unity of science (1840), which is based on the epistemological reduction. Falsification of theories was emphasized by Popper (1934) and the progress of science in the form of revolutions was described by Kuhn. He also introduced the term paradigm to describe the present worldview of scientists, which they unconsciously defend although it is sometimes shown to be wrong. Abduction was developed by Pierce (1878) and strong inference was devised by Platt (1964) [31]. Polanyi (1966) defined the term “tacit knowing”. Simulations became possible when the first electronic computer called Electronic Numerical Integrator and Computer (ENIAC) was ready in 1946. The metric system was adopted in France in 1799 and it became popular also in other countries [42]. The International Bureau of Weights and Measures was founded in 1875. In 1960 the metric system was changed to the International System of Units (Système International d’Unités, SI). Recently, an attempt to make science automatic was published in [43].

V. RESEARCH METHODS: SYSTEMS APPROACH

In the systems approach we admit that interactions between parts of a whole create emergent phenomena. This is especially valid for nonlinear systems, which cannot in general be separated into independent parts. Some nonlinear systems are separable. 

A system is “a set or arrangement of things so related or connected as to form a unity or organic whole” [44]. A pure set is not a system, which is formed by the relationships between the parts. Systems are divided into hierarchical systems and network systems [40, p. 50]. In hierarchical systems a serial organization is used. In network systems parallel organization is used. There is much redundancy and no
top and bottom. Our brain is an example of network systems. In engineering modular hierarchical architectures are preferred to network systems having an integral architecture that is difficult to design.

Hierarchies include nested hierarchy and successive layers in a layered pattern. Most systems use a nested hierarchy [12, pp. 74–82], for example an organism consists of molecules that consist of atoms that consist of elementary particles. This is an example of ontological reduction. Some systems form a layered pattern of successive layers [45, pp. 26–30], [46, p. 184–185] where lower layers offer services to upper layers. An example of this hierarchy is an organization chart.

The world is fundamentally stochastic as in the quantum mechanics, which is the theory of the microworld. This forms Hume’s problem of causality in modern terms. The macroworld looks for most engineering purposes deterministic and causal although sometimes chaotic if studied carefully enough [13, p. 316], [40, pp. 71–87]. Deterministic system models may include a random part, for example in the form of noise.

Analytical approach has severe limitations. This can be seen if we consider $M$-body problems in physics. An analytical solution for the two-body problem was derived by Newton (1687). The system of two bodies corresponds to a feedback system where a causal relationship proceeds in two directions [11, p. 256]. $M$-body systems are potentially chaotic. Sundman (1906, 1909) proved the existence of a solution to the three-body problem [47, pp. 542–544], but $M$-body problems are in general mathematically intractable although they can be easily simulated. If the $M$-body system can be divided into a set of two-body systems loosely coupled with each other as in our solar system, a solution can be found using the theory of perturbations by Laplace (1799). In one extreme, if $M$ is large and the bodies are weakly interacting with each other and proceed randomly, we can use the theory of statistical mechanics.

We conclude that we can analyze two extremes (Fig. 6): simple deterministic systems and random systems. There is no general theory for complex deterministic systems that are not chaotic because of complicated strong interactions between the parts. Many deterministic nonlinear systems tend to be chaotic and they can be analyzed statistically by using chaos theory [40, pp. 71–87]. In chaotic systems there are some patterns in the state space called attractors, including fixed points, limit cycles, and quasi-periodic and strange attractors. We can assume that our solar system is in a limit cycle.

Figure 6. Limitations of analysis

The basic resources such as materials and energy are taken from nature [11, p. 163], [35, p. 10], [12, pp. 82–92], [5, p. 477], [48, p. 29]. After their use, materials and energy are returned to nature as waste. Information and capital are abstract forms of resources without which no system could be produced. Systems use information for control [12, p. 83] so that a limited form of intelligence can be implemented. Money is essentially a deposit of work that can be exchanged to new work to design and build a new system from its parts. On the other hand, users measure system properties or performance by using functionality, reliability, convenience, and price, in this order [49, p. 227].

Resources are scarce [40, p. 159]. Our aim in engineering is to develop new functionalities and to maximize the efficiency in the use of resources so that we can improve performance and minimize complexity. These are somewhat conflicting aims. Performance is “the manner in which or the efficiency with which something reacts or fulfills its intended purpose” [18]. Complexity is in general measured by the number of parts and their relations, but fundamentally the goal is to minimize the use of basic resources for a given performance.

An order of parts is a structure [11, p. 27]. Structures can be static or dynamic [50]. Static structures represent timeless
order and they do not change with time, but dynamic structures are changing with time. An order can be timeless, sequential, or generative [50]. A timeless order is an order that does not change with time. A sequential order is a temporal order where time is included to describe successive changes. A process is an example of dynamic order which is defined to be “a series of changes with some sort of unity, or unifying principle” [8, p. 760]. In project design a sequential process is described with a waterfall model where the project is divided into rather independent phases [51, pp. 26–29]. Another model is V model where the specification and design phases are done top-down, but the implementation and validation phases are made bottom-up.

The generative order is “a deeper and more inward order out of which the manifest form of things can emerge creatively” [50, p. 151]. In practice, especially a research project is generative and highly iterative with complicated internal relations [50]. In the generative order time does not have priority. In project design this kind of process is approximated by the spiral model: the whole process is repeated and each time the result improves. A sequential order can be reduced to a timeless order, but a generative order cannot due to the internal relations; it is something between the timeless and sequential order.

Systems can be described at different levels including functional, behavioral, and executive levels [51, pp. 49–55]. The functional model is a structural or topological model where the structure is expressed using functions and relations between them. A behavioral model describes the internal behavior of the functions and therefore specifies the algorithms for the functions. The executive model is an implementation model that specifies the physical parts of the system.

There are certain fundamental limits that cannot be crossed, for example the speed of light or the lowest absolute temperature [52]. Some design problems are difficult to solve because there is no unique performance metric, different requirements have different priorities, the complexity of exhaustive search may depend exponentially on the size of the problem, the solutions are heavily constrained, the solution varies with time, and models are too simplified [36, p. 11].

System theories have been hard to develop. They include for example classical system theory, theory of nonlinear systems, decision theory and game theory within it, queuing theory, information theory, estimation theory, control theory, topology and graph theory within it, and computational complexity theory of computer science [11, pp. 19–23, 90].

Information in the form of symbols can be presented on three conceptual levels, which are the syntactic, semantic, and pragmatic levels, upwards from the bottom [8, pp. 863–864]. The syntactic level deals with internal relations between symbols just as grammar in a language. The semantic level considers the meaning of the symbols, i.e., their relationship with reality. The pragmatic level includes the utility and value of symbols. All engineering products are on the syntactic level.

Open problems in engineering include for example general theory of systems [11], semantic information theory [12, pp. 284–285], and network information theory [53, pp. 509–611]. Classical system theory is limited to simple feedback systems.

Shannon’s statistical or syntactic information theory does not cover the meaning or semantics of information. Frame problem is part of the semantic information theory: how a machine can decide the context or frame of reference. Furthermore, the statistical information theory covers only isolated links. Network information theory is not easy to develop because of the interactions of users through interference. Therefore, so far the most successful design approach has been to minimize the interference by using orthogonal or noninterfering signals as much as possible.

**History.** The history of the systems approach is summarized in [12]. Systems approach has been used since the antique, but modern systems approach including systems analysis and engineering is a rather recent development. It started in the 1940s [11, pp. 10–17, 90], [9, p. 7] and its development has been rather slow, partially because of the limitations of our analytical
tools. Thus the systems approach is often only descriptive.

Typical problems and mistakes. Typical mistakes made by a doctoral student include the following: Research problem is not defined properly and the work is too wide and cannot be finished in a reasonable time. The hypothesis is not concrete enough and cannot be tested. The student is too introvert and does not discuss with people with different backgrounds to find new ideas. Existing literature is either not studied at all or in one extreme all the time is used for studying literature. We really cannot read everything. The student does not present any intermediate results or writes too comprehensive technical reports instead of own publications. The student may publish all the time at low-level conferences where the requirements are modest and thus the possible problems are not noticed.

VI. FINAL RESULT: SCIENTIFIC PUBLICATION

Scientific papers are written to distribute knowledge, to improve the quality of the research, and as a measure of scientific merit of the researcher and the employer. The scientific knowledge is freely available. The quality of new knowledge accepted to journals and conferences is controlled by a peer review process.

The general aim in documentation is reproducibility of the experiments; no implicit assumptions are allowed. The length of the final manuscript is typically five pages for conference papers. Manuscripts for journal papers are usually written using double spacing. For letters the manuscript is 5–7 pages and for full papers it is 20–30 pages. A doctoral thesis is a special technical report having normally 50–200 pages [54, p. 67] and 100–200 references. When writing the manuscript one of the most important things is to think of the readers. Do not write the manuscript only for yourself. In this way you can avoid most of the mistakes.

Publishers usually have their own writing instructions, which must be followed. Excellent instructions are published by the IEEE. They can be used even though you publish for some other publisher if you also take into account the formal requirements of your publisher.

A scientific paper has almost always the IMRAD structure where the acronym comes from the words introduction, materials and methods, results, and discussion [23]. The full manuscript therefore includes the title and the names of the authors, an abstract, a glossary of symbols and abbreviations, which is needed only in some extensive review papers, introduction, materials and methods, results, discussion or conclusions, acknowledgment, references, and biography.

Good hints on the contents of many parts of the paper are in the original IEEE instructions [55], [56]. The instructions include a list of topics that should be included in the abstract, introduction, and conclusions. Discussion may appear before conclusions. Discussion is usually more general and conclusions more focused.

The title should be brief, clear, and descriptive, less than ten words [55]. This is the first place where you meet your readership. Novelty should be emphasized. The title should not be too general, otherwise it is not interesting to anyone.

The list of authors is one of the important parts of the paper because here you give the credit to your collaborators. You should include those who had scientific contribution, i.e., those who solved engineering problems [15]. The order of the names reflects the significance of the contribution. The first name is by far the most important. Usually only the first three or four names are considered relevant. You should give also the name of your employer, also called affiliation. If your employer was changed from X to Y during the preparation of the paper, you should write in a footnote “NN was with X. He is now with Y.”

The abstract is a short one-paragraph summary of the paper. The length is typically limited to 150 words in conference papers, 50 words in journal letters, and 75–200 words in full journal papers. The abstract must summarize what the author has done, how it was done, principal results, and significance and novelty of results [55], [56]. The results should be given numerically when possible. The first
sentence is the topic sentence, as in all other paragraphs, and it establishes the context and scope of the paper.

In the abstract important ideas should be identified. The abstract should be informative, not only descriptive. The abstract must be understood independently and it should include neither references to the paper nor obscure abbreviations. All information given in the abstract must appear also in the paper. Below the abstract usually about four key words or phrases are given.

In the introduction you must motivate the reader to continue reading. In the introduction you describe the problem, previous related work, the purpose, significance, and novelty of the paper, the method by which the problem is approached, and the organization of the paper [55]. A simple block diagram is often useful for orientation. The new contribution is shown with a brief literature review. An explicit novelty claim must be given: compare your results with the earlier results and show what is improved. Define carefully the scope of the text and find the right focus. Own results are not presented in detail in the introduction.

The materials section usually includes the “theory” needed in the paper: definitions, system model, and the related assumptions including performance metrics. The literature review in the introduction is part of the materials. An extensive literature review can be written in a separate section, but usually a separate section is not needed except in your thesis. In the methods section you describe the nomothetic or constructive methods [14], the rules of the analysis, and the rules of verification and validation unless they are trivial or well known in the field.

The results must be your own results and they may be analytical, simulation, or measurement results. It is important to present some numerical results and compare them with the literature. For statistical results not only the average should be given, but also uncertainty in the form of coverage interval and coverage probability, which is also known as level of confidence [33, pp. 25–28]. In measurements the SI system must be used.

Models are usually needed for the environment. To make results comparable, standardization organizations have defined some standard models to be used. Simple analytical limiting cases may be presented to obtain reference values and to cross-check your other results. The value of your results depends on how well they can be generalized. The bottom-up approach helps you in this.

In the conclusions you briefly summarize your work and its significance, show limitations and advantages, describe applications of the results, and give recommendations for further work [55]. Usually readers read first the title, the abstract, introduction and conclusions. Therefore these parts must be written very carefully.

The acknowledgment section should not be forgotten. You can mention those persons whose contribution was not enough to select them as coauthors [15]. Funding organizations and projects are mentioned either here or in a footnote on the first page, depending on the publisher.

In the list of references you should mention all the relevant references you used in the preparation of the manuscript. The list links your work to earlier work and through citations your work will be linked to later work. Usually the length of the list must be limited due to space limitations. Your own contribution must be clearly shown by carefully selecting the location of the references.

Plagiarism and self-plagiarism are strictly forbidden. Manuscripts that contain a crossover of more than 25 % with another manuscript by the same authors may incur sanctions [57], [58]. A conference paper can be published as a journal paper, but it must usually be substantially revised to meet the technical standards maintained by the journal [59]. The earlier paper must be clearly mentioned in the new paper. Usually no new results are requested, but up to 30 % of new material may be needed, including expansions of key ideas, examples, elaborations, etc. [60]. If the publishers are different, you must obtain a permission for the reuse from the original publisher. Quotation marks are used for verbatim quotations, otherwise the quotation must be paraphrased.
It is usually best to refer to original papers. Sometimes you can refer to a book or review paper to shorten the list. For books the relevant page numbers must be given. References to the Internet should be minimized. The reason is that most documents on the Internet are not permanently available or they may be changed. The documents are also usually not peer-reviewed.

A mind map may be useful for organizing the text. The text can be drafted in two different ways. If you do not know the topic very well, it is best to write a draft of the whole paper and try to improve it. If you know the topic well, you can make detailed drafts of the table of contents and finally you finish the sentences. The grammar is checked from grammar books and spelling of the words from dictionaries.

In the final manuscript everything must be explicit and reproducible without any silent assumptions. Top-down deductive approach should be followed. Causal explanations are preferred. The terms, symbols, and abbreviations must be unified and defined. It is best to write a stand-alone document, which can be understood without first reading the references. No gaps or contradictions are allowed in reasoning.

The most typical mistake in writing is that the novelty is not clearly shown. The novelty claim is the hardest part of any paper but also the most important from the reviewers' perspective. Other mistakes are possible: Writing instructions of the publisher are not followed, the organization is bad, and there are repetitions or gaps in reasoning. Standard terminology is not used or it is not uniform, and not all new terms, abbreviations, and symbols are defined. There are grammatical and spelling mistakes and long complicated sentences, and short inaccurate comments are included in parentheses. Equations are not properly written according to the italicization and bolding rules, figures are inaccurately drawn, and references are not properly used. An inexperienced author may want to write a textbook although in any original work he or she should write for experts. The major mistake was mentioned already in the beginning of this section: the author writes to himself or herself by not taking into account the knowledge the average reader has. The same problem is also common in seminars.

Conferences and journals should be selected carefully. You should publish in places where similar relevant papers have been published earlier. Thus it is best to check your literature review. The best possible forums, usually those of scientific societies, should be selected depending on the maturity of the idea. You should start from workshop and conference papers and work towards archive journal papers. This approach is just the opposite that you use in searching literature. Conferences can be compared with each other by using acceptance ratios, i.e., the ratio of the number of accepted and submitted papers. In good conferences it is 30–45%. Small focused conferences may be useful in finding contacts to other researchers in the field. Conferences are usually organized each year at about the same time of the year. You can make a conference calendar showing the deadlines and dates of the most important conferences.

Journals can be compared by using the average number of citations per article, but citations as a quality criterion have many weaknesses: the citations include citations to the same journal, called self-citations, which creates the problem of charmed circles; review papers are simpler to read and they may receive more citations than original papers; some significant results may not be initially easy to understand and they are forgotten for a long time; some citations may be negative and thus controversial or even erroneous results may receive more citations than other results; citations have a skew meaning that most of the citations are given to a few papers; and new journals have not yet received many citations and thus they must be separately considered. The best journals can receive significant amount of citations during 10–25 years. The average number of citations for original papers may be up to 30–70 citations, in the best review journals in engineering up to 100-180 citations.

Scientific papers are peer-reviewed [61]. This means that at least two or three anonymous reviewers or referees that are your peers read and comment and criticize
the manuscript. Usually a few iterations are needed before the manuscript can be published. In journals it is best to prepare a letter to the reviewers to answer all their comments. The reviewers tend to recommend papers that follow the present paradigm. New paradigms need careful explanation of research methods and strong empirical evidence [23].

The decision is made by an editor organizing the review in the journal. In conferences the decision is made by a technical program committee. The criteria for acceptance of scientific papers and doctoral theses include novelty, significance, correctness, and readability. The value of the manuscript can be estimated by using the criteria for science, i.e., agreement with reality, as verified with the hypothetico-deductive method, coherence, generality, and fertility [34, p. 109].

History. Peer review started in 1675, soon after the publication of the first scientific journals, but it took a long time before it was a common practice. In physics that happened in the 1950s [62]. The methods section was added to scientific papers by Pasteur in the middle of 1800s [23]. A document preparation system for mathematical texts called LaTeX is based on the TeX typesetting program by Knuth (1977) and was developed by Lamport in 1986.

VII. Conclusions

Research starts with a problem statement. After the initial collection of data a hypothesis is formulated and then refined and verified by using the hypothetico-deductive method. In engineering research a performance criterion is often defined and a system is optimized.

Research is a demanding learning process where nobody initially knows the solution, otherwise it would not be novel. Bibliographies should be used to improve the efficiency of literature reviews. After a few iterations between references and citations you will be quite certain that you have the relevant state-of-the-art books and papers. The terminology should be learned and a taxonomy of relevant concepts must be formed. The problem and hypotheses are found by using a bottom-up experimental-inductive method based on methodological reduction. The term “induction” does not clearly describe the formulation of the hypothesis and sometimes a more general term called abduction is used. Strong inference refers to the use of several competing hypotheses from which the best is selected.

The scientific method uses the principle of analysis and synthesis. We divide an existing whole into parts and build from the parts something new, first something rudimentary as a single transistor and later more complicated wholes step by step. We may study an existing theory by using analysis, but to develop a new theory we must analyze the properties of the whole and propose a theory by using the bottom-up approach, by improving the theory step by step. We must therefore combine the top-down and bottom-up approaches, i.e., “we break down and put together”.

The criterion for the reliability of knowledge is not the opinion of authorities but coherence and correspondence with reality. The truth is seen unattainable. In documents it is essential to use the top-down deductive approach and the IMRAD structure emphasizing causal relationships. The paper should be outlined right from the beginning since there will never be “more time”.

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