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BREAKTHROUGH TECHNOLOGIES: ANALOGIES, SCALABILITY, TECHNOLOGY-DEPENDENT PHYSICS

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INTRODUCTION

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- Diploma in aerospace engineering from Technical University of Munich (TUM), internship at ESA
- PhD in space systems engineering (TUM, visiting researcher at MIT Systems Architecture Lab)
- Postdoc at LGI – CentraleSupelec: Complex systems engineering – eco industrial parks, product service systems for autonomous cars
- Co-founder of the non-profit Initiative for Interstellar Studies (i4is): development of advanced space systems (femto-satellites, interstellar missions)

WHAT ARE BREAKTHROUGH TECHNOLOGIES?

Breakthrough technologies are technologies that introduce **radically new capabilities** or a **performance increase** of **at least an order of magnitude**.

Examples are the turbojet, inertial navigation, and autonomous driving.

- Why are breakthrough technologies important?

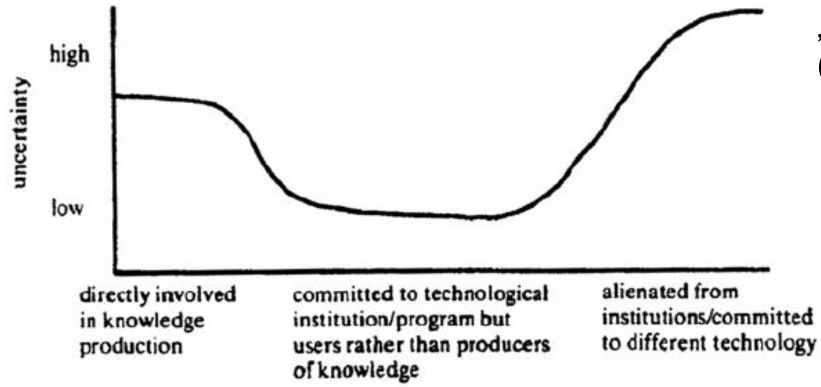
  Rare but can have a large impact on companies, societies, etc. (google search engine, pocket calculator, airplanes, autonomous cars)

- Why are they different from "ordinary" technologies?
  - Breakthrough technologies usually introduce a new technological trajectory, as their performance increase does not result from an extrapolation of existing technologies (incremental innovation) but radical innovation (system architecture and component technologies are heavily impacted) (Henderson & Clark, 1990)

- What makes **potential** breakthrough technologies interesting in terms of models?
  - Many unknowns: Does it work at all? Is there a market? Is it going to be accepted?
  - Rather exploration (new knowledge creation) than linear development (application of existing knowledge)
  - "Paradigm shifts" → Radical change of underlying models → New models need to be developed to create knowledge

PREDICTIONS OF BREAKTHROUGH TECHNOLOGIES

- **Inertial navigation:** „A completely impossible endevour“ (Max Schuler -„inventor“ of inertial navigation)
- **Nuclear energy:** “There is not the slightest indication that [nuclear energy] will ever be obtainable. It would mean that the atom would have to be shattered at will.” (Albert Einstein)
- “we cannot control atomic energy to an extent which would be of any value commercially, and I believe we are not likely ever to be able to do so.” (Ernest Rutherford)
- **Heavier-than-air flight:** „not the smallest molecule of faith in aerial navigation other than ballooning.” (Lord Kelvin, 1896)
- **Electric light:** British parliamentary commission with notable physicists deems it impossible.
- **Continuous-aim firing:** US Chief of Bureau of Ordnance – mathematically impossible



„Certainty trough“
(MacKenzie, 1993, p.372)

TECHNOLOGY DEFINITION

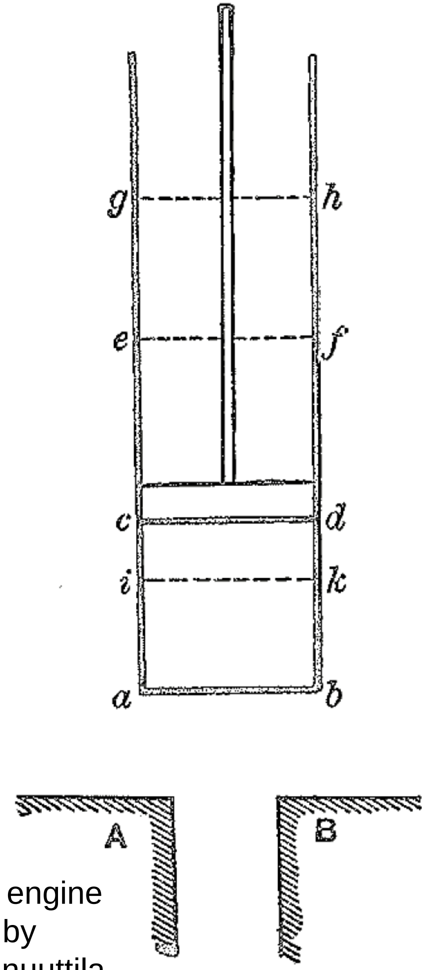
- Defining what **technology** is:
  - Technology as **knowledge** (Layton, 1974)
  - Knowledge captured in technological **artifacts** (Vincenti, 1990, 1992)
  - Technology elements: **artifact** (car, airplane), **design** (specification of artifact), **competencies** (knowledge, tools, methods, models) (Hein, 2016)
- Defining the **unit of analysis**, e.g. airplane:

  - Is it a **concrete** airplane, e.g. the Wright Flyer 1?
  - Is it airplanes **in general**?
  - Is it the **function** the technology fulfills? (flying)
  - Are **enabling systems** (e.g. maintenance workshops) and **competencies** (personnel for development and production) also included? (Hein, 2016)
- **Potential** breakthrough technologies are often less precisely defined:
  - Autonomous driving: What level of autonomy?
  - Artificial general intelligence: Unclear definition and therefore criteria for achieving AGI
- Evolution: Understanding / interpretation of a technology changes over time (Morison, 1966; Bijker et al., 1987)

LITERATURE SURVEY: PHILOGOPHY OF ENGINEERING MODELS

- Philosophy of engineering models:
  - **Boon & Knuuttila 2008:** Models as epistemic tools → Carnot heat engine, development of new concepts around a model
  - **Vincenti 1990, 1992:** Epistemic use of models in engineering activities, taxonomy of models (fundamental design concepts (operational principle + normal configuration), criteria and specifications, theoretical tools)

In the following, I consider models as epistemic (knowledge-creation) tools rather than representations of an artifact to-be



Hypothetical heat engine model developed by Carnot (Boon & Knuuttila, 2008)

LITERATURE SURVEY: SOCIOLOGY / HISTORY OF TECHNOLOGY

- Numerous case studies of breakthrough technologies in the sociology / history of technology literature:
  - **Bijker et al. 1987:** „Social construction“ of technology (electrification)
  - **Laudan 1984:** The Nature of Technological Knowledge
  - **Van den Daele 1977:** Studies in ***goal-oriented*** research (fusion reactor)
  - **Constant 1984:** Role of ***engineering communities*** (turbojet)
  - **MacKenzie 1993:** Social construction of technological feasibility for black-box navigation – Role of ***institutionalisation***
  - **Sapolsky, 1971; Greenwood, 1975:** Polaris & MIRV missile development: Co-evolution of the ***institutional structure*** and the technology
  - **Westrum 2013:** Role of ***engineering communities*** and how ***geographic context*** dependency impacts social interactions

LITERATURE SURVEY: STRATEGIC MANAGEMENT

- Impact of breakthrough technologies on firm:
  - Henderson & Clark, 1990: Why established organizations often fail in constructing the knowledge (channels and filters) for a new technology
- Dominant design (a technological „paradigm“):
  - De facto standard of how a type of artifact should be (Utterback & Abernathy, 1975, Anderson & Tushman, 1990): von Neumann architecture, Ford T, single aile airplane
- Radical innovation:
  - Change in system architecture + technologies / working principles of components (Henderson & Clark, 1990)

RESEARCH GAPS & QUESTIONS

Research gaps:

- Role of models in breakthrough technologies not yet explored: Literature on engineering models deals mostly with incremental design / innovation; Revolutionary innovations, breakthrough technologies not considered
- History and sociology of technology literature deals with breakthrough technologies; But focus on communities of practice, institutional and political context.
- Strategic management literature: Impact of breakthrough technologies considered. Role of models not considered.

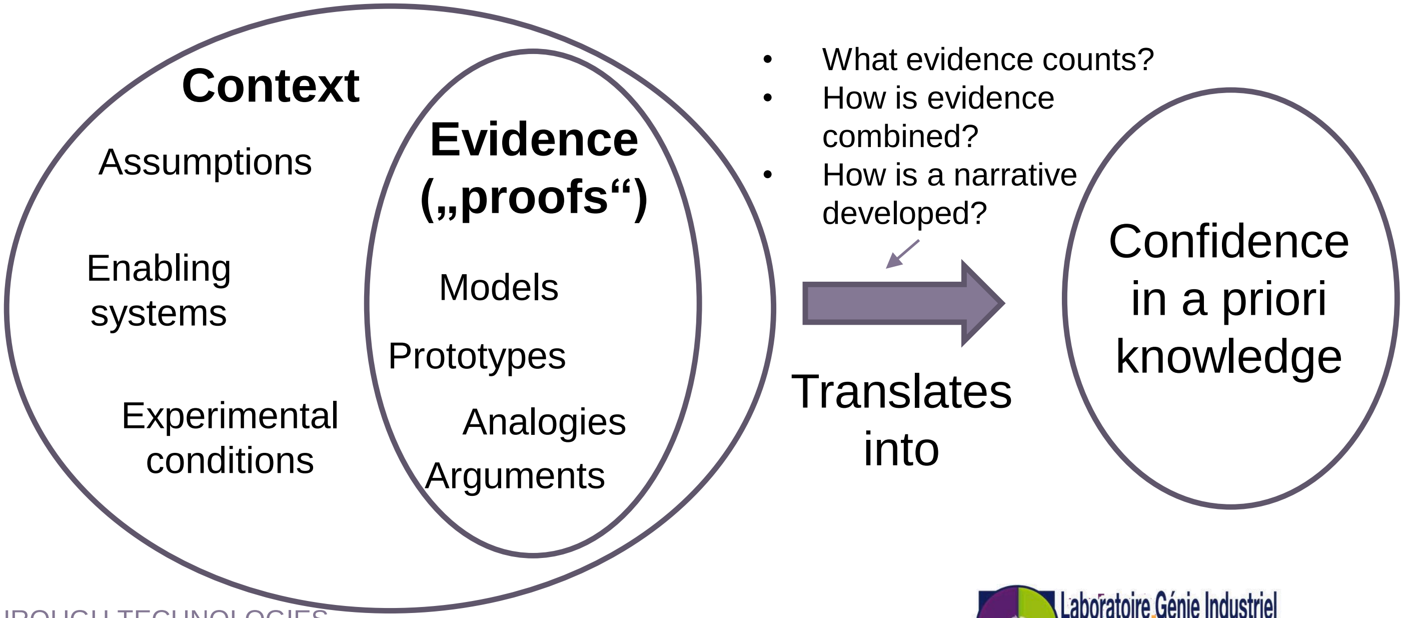
Research questions:

How are engineering models used in assessing the feasibility of potential breakthrough technologies?

What are particular characteristics of the use of engineering models in this context?

EVIDENCE – KNOWLEDGE PROBLEM

- In engineering, we want to create a priori knowledge about a domain of interest: artifact to-be, organization to-be, etc.
- We want to gain confidence in this a priori knowledge via a posteriori knowledge (prototypes, experiments).
- **Problem:** How does evidence (via prototyping, experiments, simulations) contribute to confidence in knowledge?



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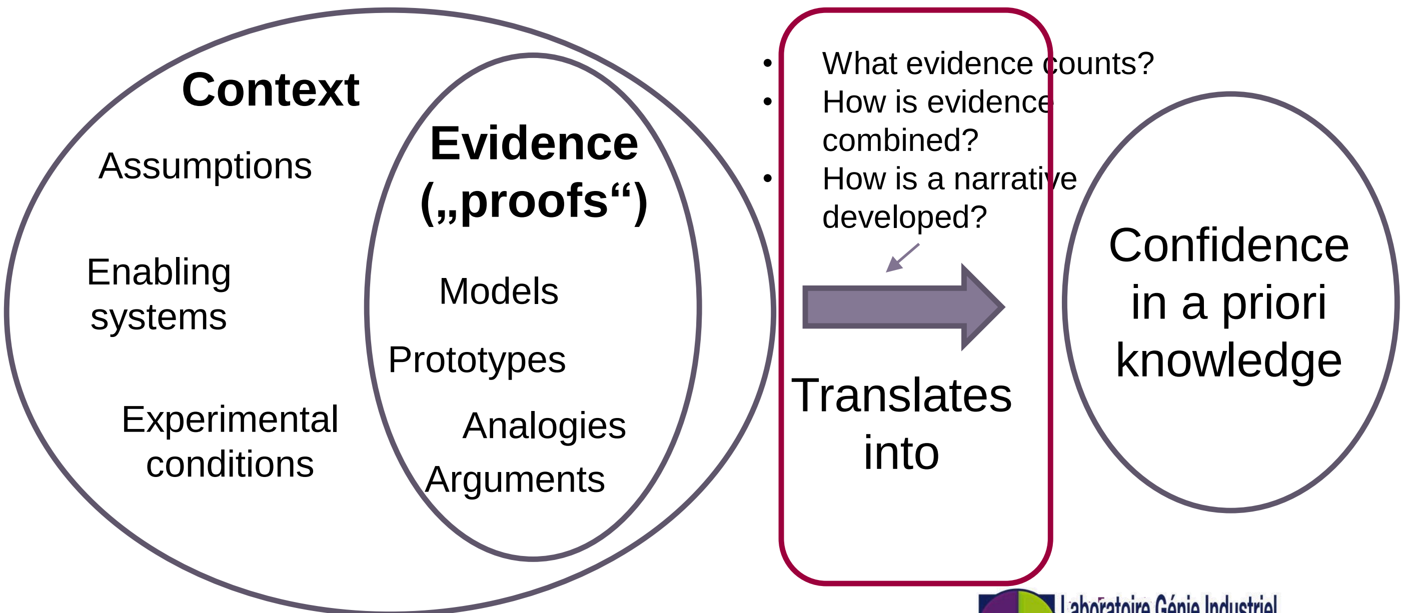


GUIDING THEMES: ANALOGIES, SCALABILITY, TECHNOLOGY-DEPENDENT PHYSICS

Models at the early, exploratory stage of potential breakthrough technologies often serve the purpose to **argument for or against its feasibility**. As the technology itself does not exist, the question becomes how to **extrapolate (generalize) from existing knowledge** and **limits to extrapolation**.

- **Analogies:** Used as „existence proofs“ for technologies, „Gedankenspiel“, TRL

x is feasible in context *y*, as it is feasible in context *z*.

- **Scalability:** The technology still “works” if one or more variables are increased / decreased. Often, technologies no longer work when new phenomena occur that are size or context-dependent, e.g. combustion instabilities. These phenomena are usually not taken into consideration in existing models and these models have to be extended or replaced. (linear vs. non-linear models for structural mechanics)

- **Technology-dependency of physics:** Some phenomena only exist because of a certain technology. The physics that describes this phenomena is therefore tied to this technology (The phenomena cannot be found in „Nature“). Physics still „the knowledge of nature“, if the phenomena are artificially created? We can no longer talk about „What remains is an engineering problem.“ when we do not know a priori that a new phenomenon occurs → Major source of uncertainty (fusion reactor)

EXAMPLE: THE WRIGHT BROTHERS AIRPLANE

Three problem areas the Wright Brothers systematically addressed:

- Aerodynamics (generation of lift)
- Control
- Propulsion (develop a light yet powerful engine)

Use of engineering models for determining aerodynamic coefficients:

- Use of wind tunnel for testing wing profiles
- Testing aerodynamic coefficients using a bicycle
- Revision of Lilienthal's and Smeaton's tables of aerodynamic coefficients

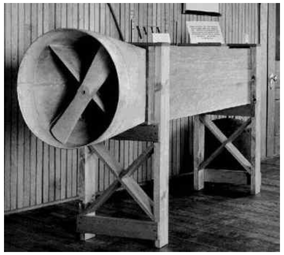
Control (warped wing design):

- Development of unpropelled gliders

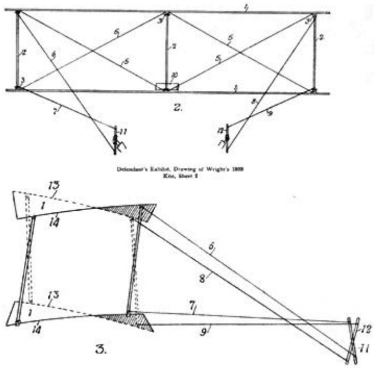
Propulsion (gasoline engine):

- In-house development

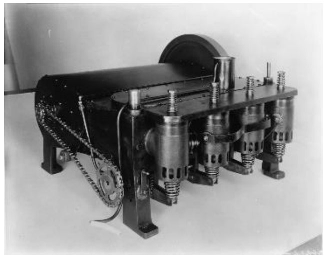
(Smithonian Aerospace Museum, Orville Wright notebooks, Gibbs-Smith, 1987)



Wright Brothers wind tunnel



Wing warping for control



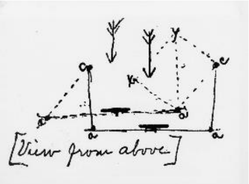
Wright Flyer engine

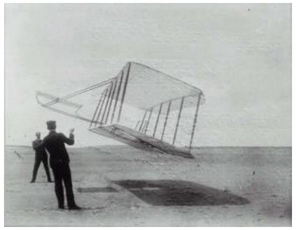
THE AIRPLANE: A PROBLEM OF SCALABILITY?

- Why were previous innovators not successful? **Small-sized, propelled airplanes existed for over a century**.
- Propulsion problem resolved earlier
- Problem of **scalability** (here: from small to large) for two key ares:
  - Airplane control: Control via shifting body weight → limits size of plane; larger planes are no longer controllable
  - Aerodynamics: How can small wings be scaled up? Knowledge of the underlying relationships

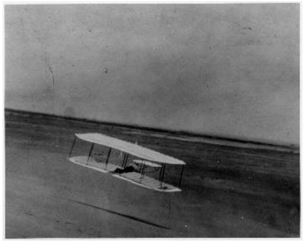
Pénaud propeller airplane in 1871

Lilienthal: control by weight-shifting

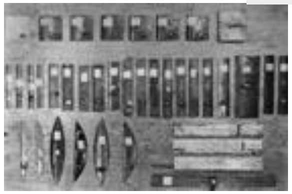


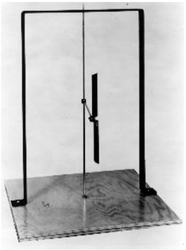


Poor lift performance of 1900 glider



1901 glider: worse performance





Systematic determination of aerodynamic coefficients (>200 wing profiles) via experiments

EXAMPLE: NANOTECHNOLOGY - MOLECULAR ASSEMBLERS

- Visionary proposal by K. Eric Drexler (80s-90s): Atomically-precise manufacturing → coined term „nanotechnology“

K. Eric Drexler

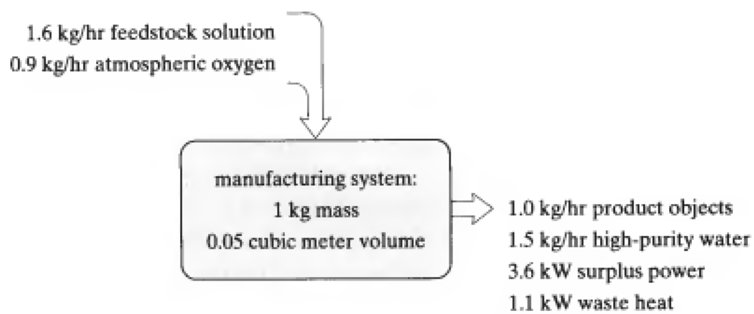
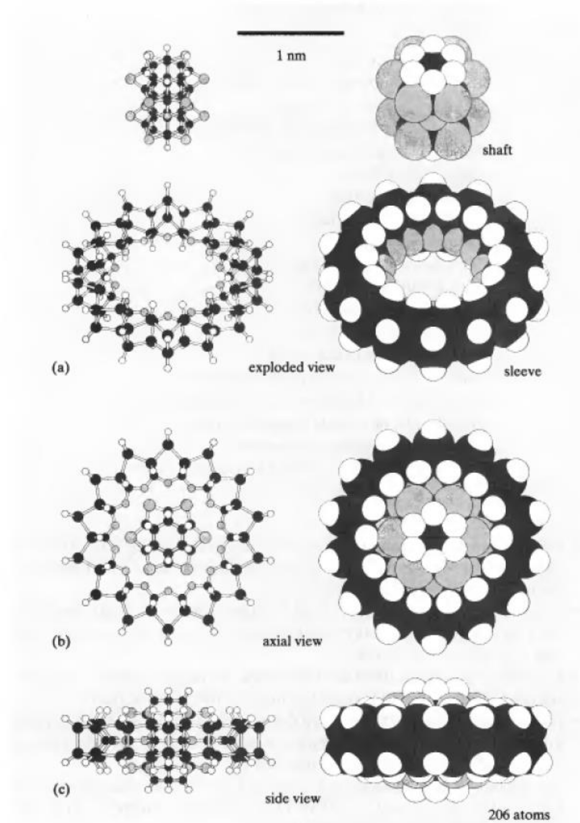


Figure 14.8. The inputs and outputs of the exemplar manufacturing system discussed in Section 14.4.

Hypothetical molecular assembly system (Drexler, 1992, p.428)



Nano-sized bearing (Drexler, 1992, p.4)

MOLECULAR ASSEMBLERS: SCALABILITY

- Scale-dependency of models:
  - Low-level molecular behavior → computationally extremely costly → Drexler uses models that neglect quantum-level behavior

Table 1.4. Levels of abstraction and approximation in molecular systems engineering.

Scale-dependency of models

Mechanical design	System behavior	Nanomechanical design
Mechanical design	Subsystem behavior	Nanomechanical design
Mechanical design	Lumped-component models	Nanomechanical design
Mechanical design	Continuum models	Nanomechanical design
	Bounded continuum models	Nanomechanical design
Molecular modeling	Molecular mechanics	Nanomechanical design
Molecular modeling	Molecular orbital methods	Nanomechanical design
	Schrödinger equation	
	Quantum electrodynamics	
	...	

Further limitations:

- Only manipulations in vacuum (no solution-phase chemistry)
- Only diamandoid covalent solids considered

- Drexler introduces a new vocabulary:
  - „Machine-phase“: Controlled molecular manipulation in vacuum
  - Molecular assemblers: Only functionally defined (manipulation of molecules) but no description of how it works

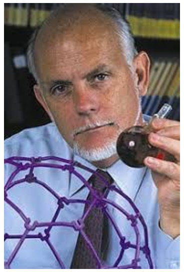
DREXLER-SMALLEY DEBATE REVISITED

- Feasibility debate between Eric Drexler and Nobel laureate Richard Smalley
- Use of **analogies** and how it can go wrong: The case of ribosomes - Argument by analogy put forward by Drexler

„**like enzymes and ribosomes**, proposed assemblers neither have nor need these "Smalley fingers." The task of positioning reactive molecules simply doesn't require them. "

Logical form of analogy: *x* is feasible in context *y*, as it is feasible in context *z*;

Positioning reactive molecules for nanomachines is feasible, as it is feasible **for enzymes and ribosomes**



„Rebuttal" by Smalley:

"Is there a living cell somewhere inside the nanobot that churns these out?"

A problem of scalability? Smalley seems to refute molecular assemblers on the basis of quantum effects between molecules. Drexler uses models that do not take quantum effects into account → The Drexler-Smalley debate seems to be also a debate about the scalability of models (When do certain phenomena need to be taken into consideration, when can we neglect them?)

EXAMPLE: FUSION REACTOR

- Paths to a commercial fusion reactor (Rose, 1971)

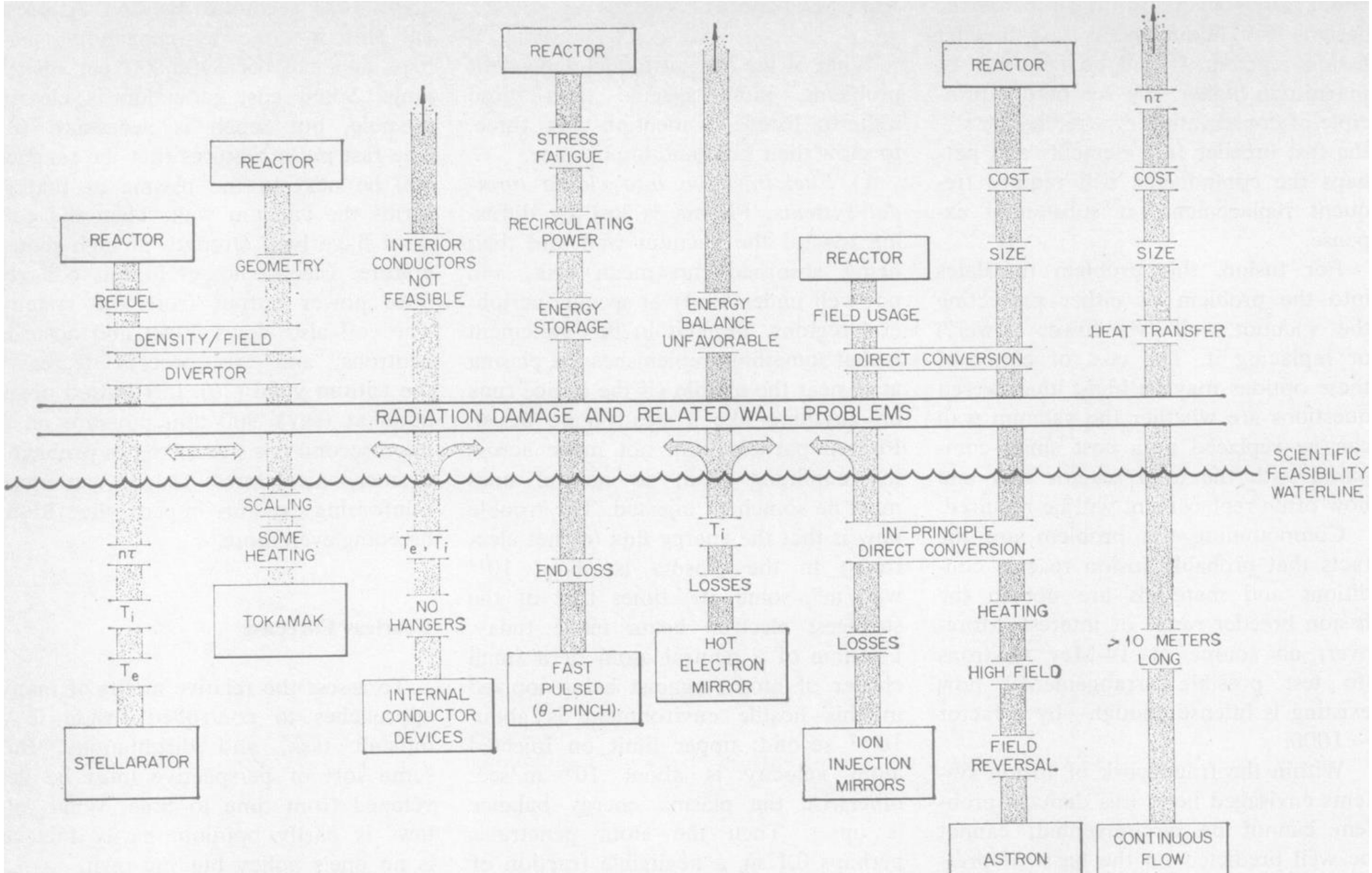
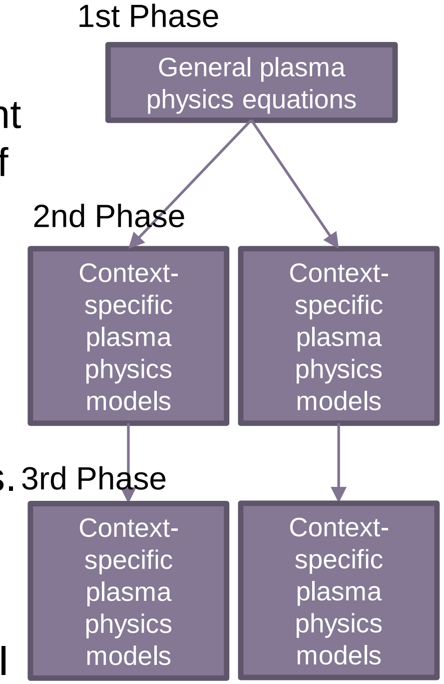


Fig. 9. Various paths to successful controlled fusion, with difficulties.

Rose, D. J. (1971). Controlled nuclear fusion: status and outlook. *Science*, *172*(3985), 797-808.

EXAMPLE: FUSION REACTOR

- Co-evolution of physical and engineering models with breakthrough technologies (fusion reactor):
  - **First phase: Project Sharewood** → The underlying general equations describing the physics of plasma behavior existed → The application of these equations to answer practically relevant questions (underestimation of plasma instabilities, interaction of plasma with wall materials, predicting experimental outcomes with sufficient accuracy) related to the fusion reactor fails.
  - **Second phase: Fundamental research** restarts with building predictive models for relevant fusion reactor aspects.
  - **Third phase: Refocus** on creating a practical fusion reactor, starting with a sufficient understanding of the relevant problems.



Conclusions:

- Metrics that capture the „goodness“ of a solution were essential (Lawson factor) for measuring progress.
- Top-down model evolution: General plasma physics model to multitude of application-specific models → ***Technology-dependence of physical phenomena and physical models***

(Van den Dahle, 1979; Rose, 1971)

PHYSICS & ENGINEERING MODELS: FUSION REACTOR

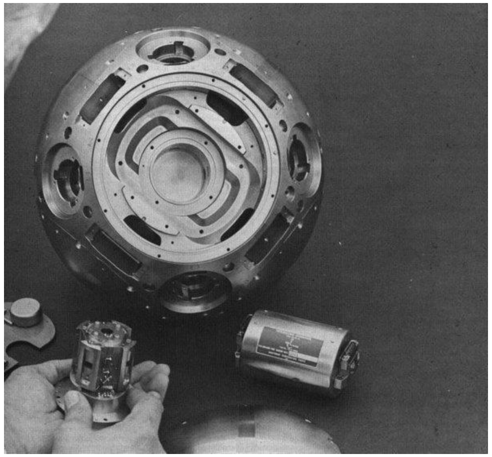
Technology-dependency of physics: Some phenomena only exist because of a certain technology. The physics that describes this phenomena is therefore tied to this technology.

Example: Plasma behavior under inpurities (wall material that ablates into plasma) in a fusion reactor does not occur in nature.

Physics still „the knowledge of nature“, if the phenomena are artificially created?

EXAMPLE: BLACK BOX INERTIAL NAVIGATION

- Black box inertial navigation: Accurate position determination without external data (black box)



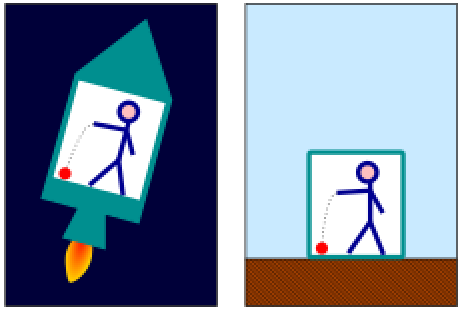
Inner sphere of MX Advanced Inertial Reference Unit

- *Importance:* Ships, airplanes, missiles all require accurate position determination without external data
- The feasibility of black box inertial navigation was a matter of debate over decades. (MacKenzie, 1993)

MacKenzie, D. A. (1993). *Inventing accuracy: A historical sociology of nuclear missile guidance*. MIT press.

MODELS AND BREAKTHROUGH TECHNOLOGIES: BLACK BOX INTERTIAL NAVIGATION

- „Problem of the vertical“ (raised by George Gamow): Challenge by an **analogy**



Logical form of analogy:
x is feasible in context *y*, as it is feasible in context *z*;

The distinction between gravitation and acceleration is **not** feasible in **black box inertial navigation**, as it is **not** feasible in context of **general relativity theory**;

→ Black box inertial navigation is infeasible

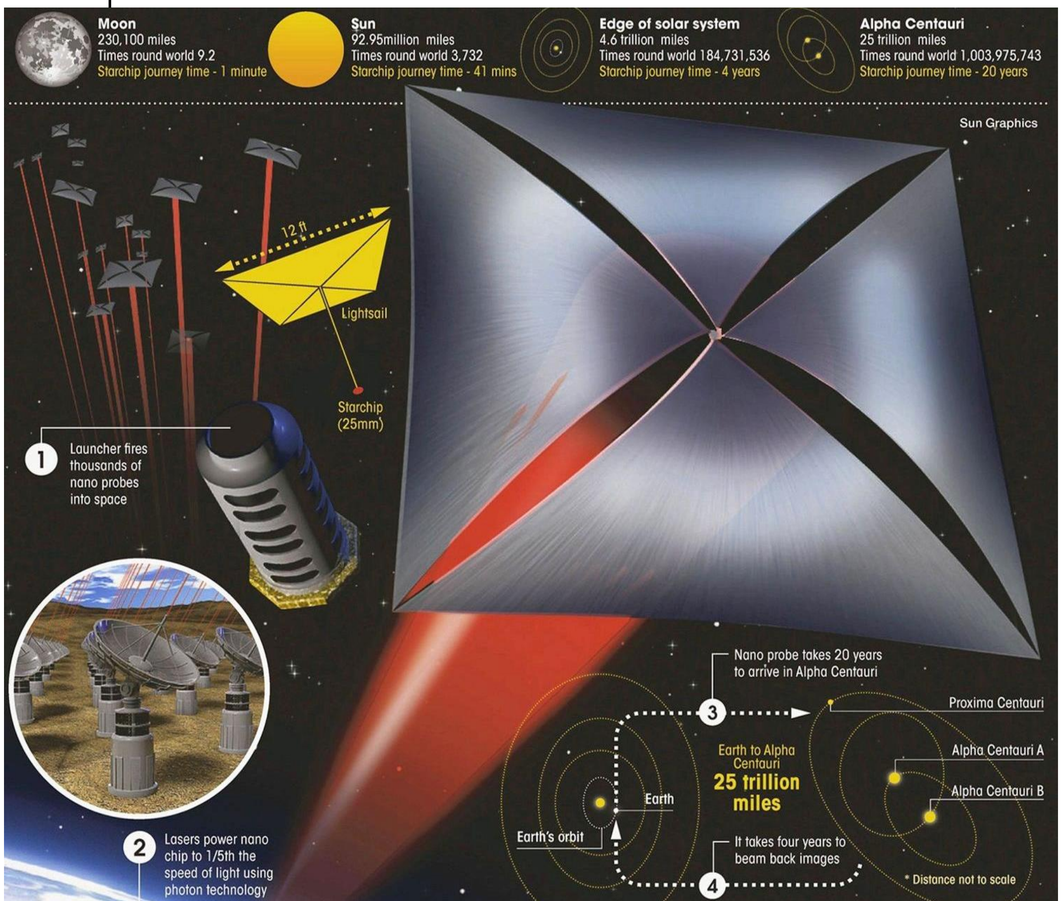
- Rebuttal of the „problem of the vertical“ (Schuler principle): Another **analogy**

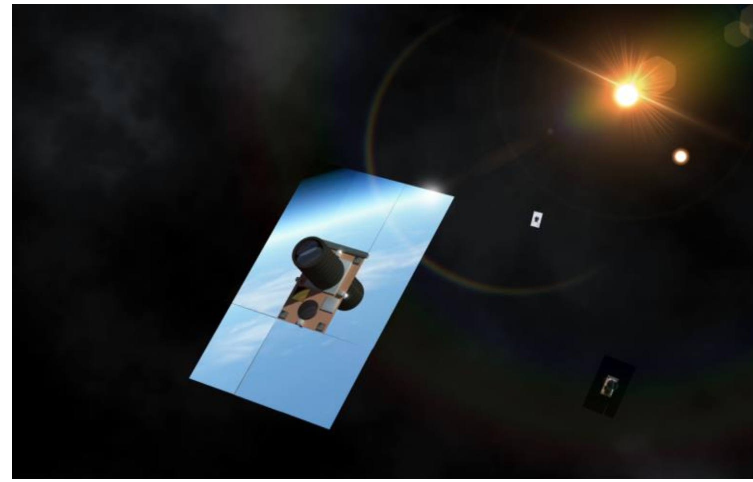
The distinction between gravitation and acceleration is feasible in a **real device**, as it is feasible with a **hypothetical Earth-sized pendulum**;

→ Black box inertial navigation is feasible

CASE STUDY: INTERSTELLAR TRAVEL

- Fly to Alpha Centauri within 25 years





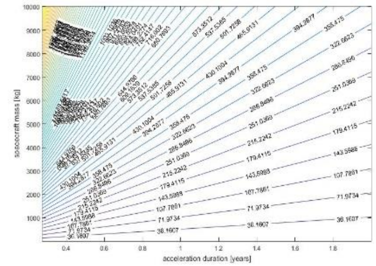
CASE STUDY: INTERSTELLAR TRAVEL

Interstellar travel: General approach in demonstrating feasibility:

1. First order estimations (Goal: Does it work at all? Back-of-the envelope calculations):
   - Use of fundamental equations: force, momentum, electric charge, photon pressure…
   - Simplify problem by using reasonable approximations (idealizations, neglect some physical effects, neglect design specifics)
   - High level requirements satisfied? → If they are not satisfied even under idealized conditions, they are likely not satisfied with more detailed models

	A	B
1		
2	Spacecraft velocity relative to Alpha [m/s]	75000
3	Distance to Alpha	4.06814E+17
4	Duration [s]	5.42419E+12
5	Duration in years	172000
6		
7		

2. Exploring the „trade space“: Search for technological alternatives and promising combinations:
   - What material is better for a laser sail? Graphene, dielectrics aluminum?
   - Is radiofrequency communication or optical communication better suited for sending data back?



Decreasing idealization, more specific technology definitions

CASE STUDY: INTERSTELLAR TRAVEL

Interstellar travel: General approach in demonstrating feasibility:

- First order estimations (Goal: Does it work at all? Back-of-the envelope calculations):
  - High-level requirements:
    - Reach the Alpha Centauri star system within 50 years from launch.
    - Fly past stars without deceleration
    - Use a laser beam as primary propulsion
  - Fundamental equations (equations of motion, equation for photon force):

    Photon force on sail: $F = m\ddot{x} = \frac{(1+R)P}{c}$

    Acceleration duration: $t_{acc} = \frac{c v_{cruise}}{m(1+R)P}$

    Trip time: $t_{trip} = \frac{s}{v_{cruise}}$

    …

	A	B
1		
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6		
7		

Excel sheet model

  - Simplify problem by using reasonable approximations (idealizations, neglect some physical effects, neglect design specifics):
    - Perfect sail reflectivity: $R = 1$
    - Laser beam inefficiencies are neglected (beam spread, jitter, diffraction, lens inpurities)
    - Sail area is neglected: Total sail area is hit by the full beam

CASE STUDY: INTERSTELLAR TRAVEL

- Exploring the „trade space“: Search for technological alternatives and promising combinations:
  - What material is better for a laser sail? Graphene, dielectrics, aluminum?
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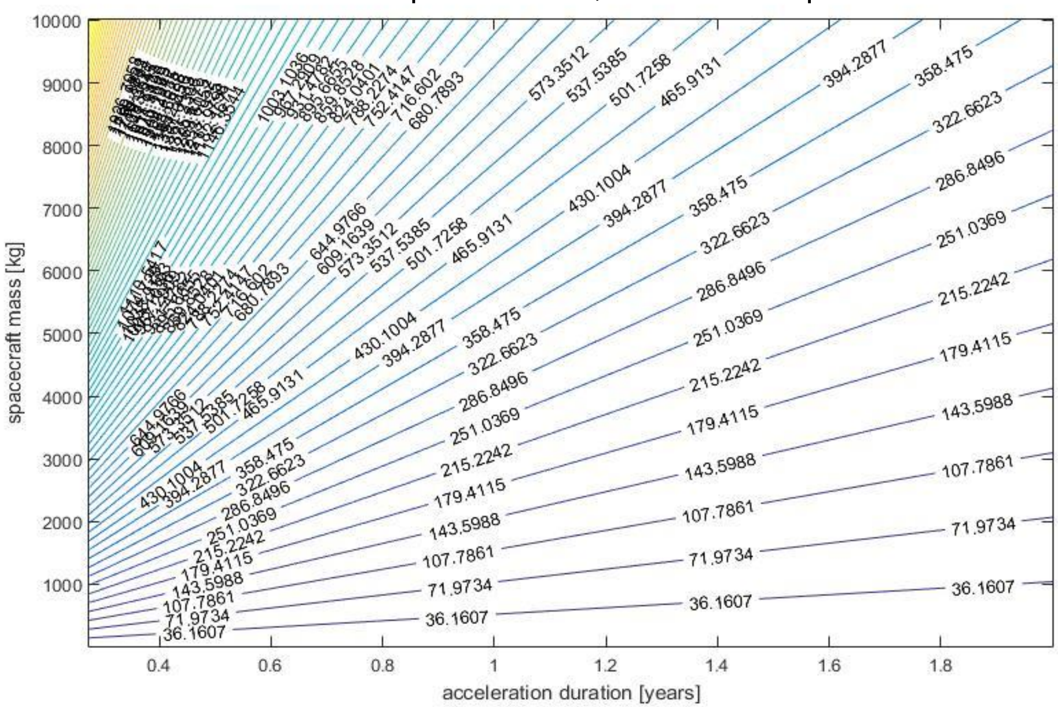
Trip time tradespace for laser-propelled interstellar mission to Alpha Centauri, 100GW laser power



Visualizing the trade space helps reasoning about positioning the architecture / design by making trade-offs:

For the same trip time we can either accelerate longer (which requires a larger laser lens) but we can launch a heavier spacecraft (more science instruments); Or we can accelerate quickly (which requires a smaller laser lens) but results in a lighter spacecraft (less science instruments)

CASE STUDY: INTERSTELLAR TRAVEL

- Exploring the „trade space“: Search for technological alternatives and promising combinations:
  - What material is better for a laser sail? Graphene, dielectrics, aluminum?
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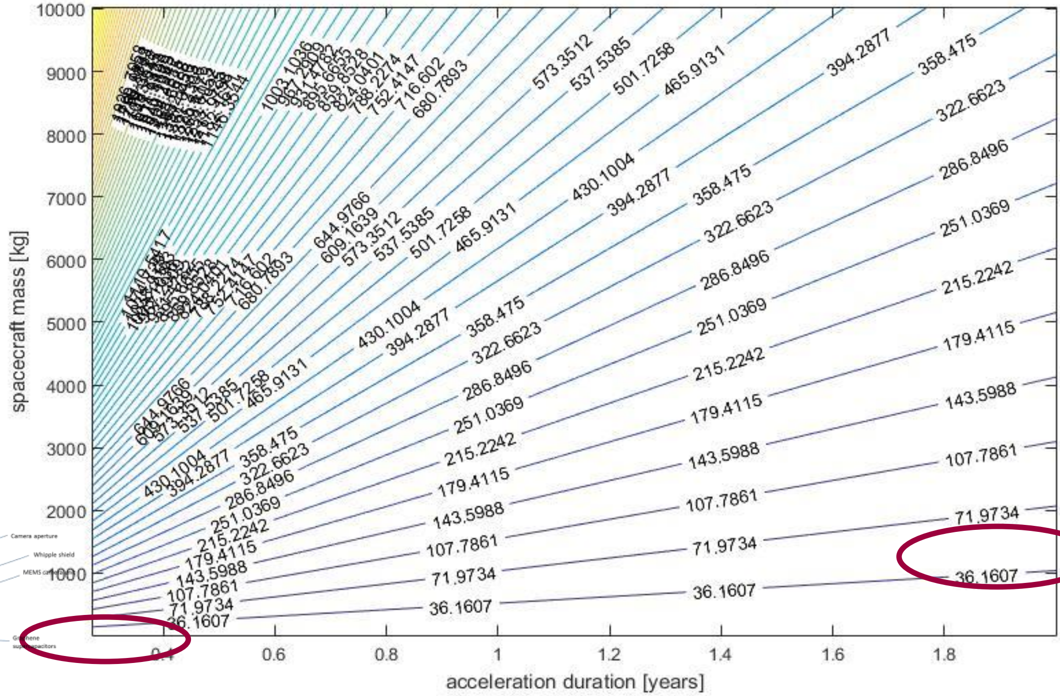

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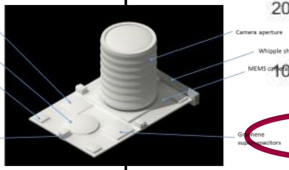
Multi-GW per m²: Do new physical effects occur?



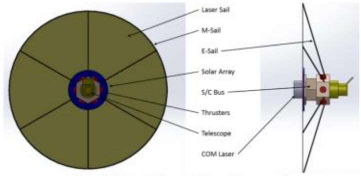


Figure 5-17: Description of the Dragonfly spacecraft

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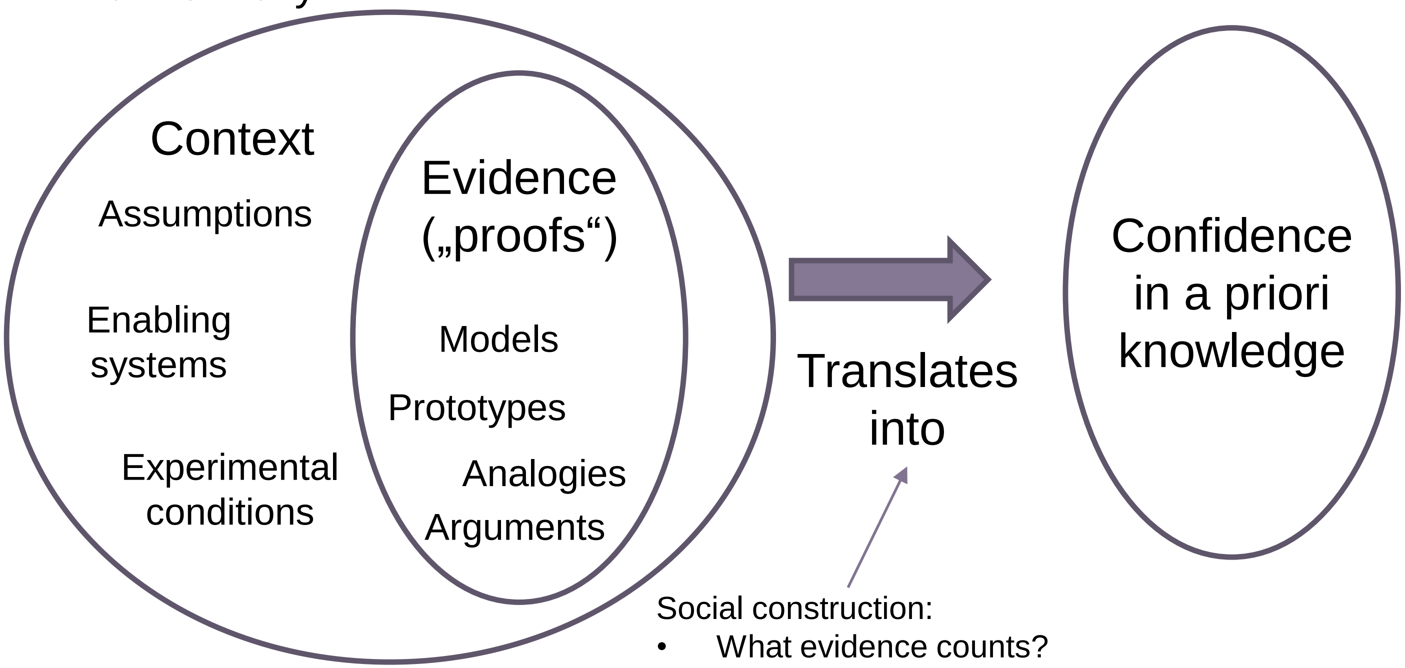
„PROOFS“ OF BREAKTHROUGH TECHNOLOGIES

- Proponents of breakthrough technologies often use notions from the exact sciences such as „existence proof“ from mathematics → Seemingly more convincing
- Relationship between „proofs“ and feasibility → the relationship is socially constructed → there is no logically neccessary relationship between the two; For example, Technology Readiness Levels are used for consensus-building rather than formally.



Social construction:
- What evidence counts?
- How is evidence combined?
- How is a narrative developed?

CONCLUSIONS

How are engineering models used in assessing the feasibility of potential breakthrough technologies?

- Models are primarily used for **knowledge-creation**, as many unknowns → More **bold extrapolations**
- Models are used for **consensus-building** within the community of practice or with stakeholders, e.g. use of analogies

What are particular characteristics of the use of engineering models in this context?

- Questions about the **validity of models** are raised more often, as breakthrough technologies often venture into the unknown (questions of scalability, context-dependence are raised)
- Initial models can be invalid, as **new physical effects** may appear → Difficult to draw a clear demarcation line: „The rest is only engineering!“
- There is **no logically necessary relationship** between a set of evidence and the technology‘s feasibility. (Similar to the induction problem in the philosophy of science)

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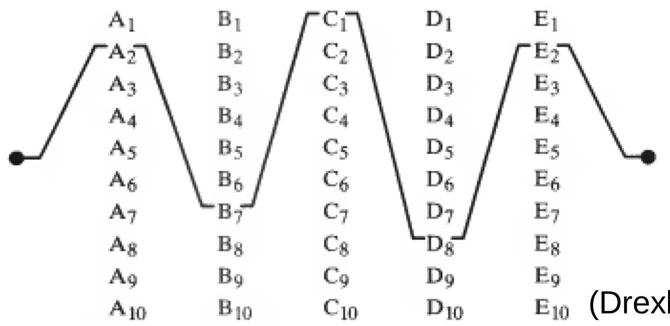
Back-up

DREXLER: EXPLORATORY ENGINEERING

- Approach developed by K. Eric Drexler: Explore feasibility limits by using physical models



(Drexler, 1992, p.501)

Figure A.2. One path through an array of many choices: if only one choice is correct at each step, then only one of the 10^5 possible paths can be correct. If none of the known choices for some step is correct, then no path can be correct.

According to Drexler, a hypothesis in science fails if one of its constituent elements has been proven false.

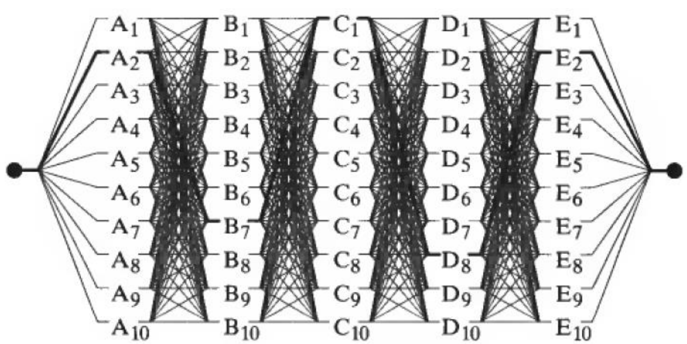


Figure A.3. Many paths through an array of many choices: if many choices are likely to be correct at each step, then many (though perhaps a small fraction) of the 10^5 possible paths are likely to be correct.

(Drexler, 1992, p.502)

In engineering, usually many options exist at each step of development. Hence, you can not rule out the whole technology if one option turns out not to be feasible.

TECHNOLOGY AS MONUMENTS: ABOUT THE LIMITS OF ENGINEERING KNOWLEDGE

- The discoursive structure underlying technologies is only partly rational (accessible to arguments, e.g. Why was this wing shaped like this? Because …):
  - Path-dependence („history matters“): Any technology already comes with a bag of history (decisions, rationales, how it was used, …). This history determines (at least partly) how the technology evolves.
  - Arguments are also rather used to rationalize a posteriori technological facts
  - Technological knowledge is intimately related to value judgements (any decision involves value judgements). These value judgements can only be partly rationalized, or made explicit.

- In analogy to Foucault‘s „Archeology of Knowledge“ we can treat technologies as „monuments“. Instead of a coherent „story“ we can tell about a technology, it is a collection of fragments, discontinuities that can be treated as a monument, inaccessible to a full rationalization.

(Foucault: Archeology of Knowledge)

TRIAL AND ERROR VS. SYSTEMATIC SEARCH

- Could the modern approach to engineering (define measurable performance parameters and systematic development of explanations that have predictive value (e.g. equations, simulation models)) contributed to the drastic increase in economic productivity?
- Example: Steam machines did only improve when a theoretical model for the ideal steam machien (Carnot cycle) was developed, contributing significantly to industrialization.

UNDERDETERMINATION OF MODELS

- Underdetermination in the philosophy of science:
  - Theory is underdetermined by the empirical data → There are degrees of freedom in how a theory can be formulated w.r.t. the data
- Underdetermination of engineering models (models used for a practical purpose): The model itself is underdetermined w.r.t. its context → Additional contextual information is required for an adequate application.
- Observations from model reuse projects:
- Numerous research projects have tried to build up model libraries for reducing the time to create models.
  - A common observation is that contextual information for these models is a must-have for getting engineers to use these libraries:
    - In what context is the use of this model appropriate?
    - How do I interpret its results?
    - What are the limits?
    - Which factors were omitted and which were taken into account and why?
  - Other examples: „architectural mismatch“ for reusing software components, difficulties of „meta-studies“ stem mostly from clarifying assumptions underlying the statistical model

GAP-FILLING

- When contextual information is missing, inherited (path-dependent) assumptions are used to fill the gaps. → Inadequate mental models, in particular when confronted with new situations.
- Psychological necessity to embed something new into an existing framework. (Maybe to make people more comfortable with an idea)
  - First tanks: „Landship“ to evoke similarity with naval vessels, armored cavalry
  - Molecular nanotechnology: Use of „cell“ and DNA analogy
- Drexler-Smalley nanotechnology debate: Smalley takes the cell analogy literary and questions the feasibility of molecular nanotechnology.

TACTICS FOR GAP-FILLING

- Arguments by analogy

x is feasible in context y, as it is feasible in context z;

Self-replicating in nanomachines is feasible, as it is feasible for biological cells

- Metaphors

x is like y, y has attribute z, hence x can have attribute y

DNA is like the book of life. As a book can be read, DNA can be read

- Arguments bound by context:

x is infeasible, as it has been shown infeasible in context y

Continuous aim firing on ships is infeasible, as it has been shown infeasible for a coastal gun

→ Literature on arguments by analogy

→ Literature on formal definition of metaphors