Engineering and Science: How They Differ, and Why We Need This Difference

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1. Outline of the Talk

- *Idea* (Tchoshanov): clearly distinguish between "engineering" and "scientific" parts of education.
- *Situation:* this idea is not yet universally accepted.
- *What is needed:* a better understanding of the main ideas behind – and the need for – this distinction.
- *What we do:* we overview how (and why) natural sciences and traditional engineering are separated.
- *How we do it:* we describe the ideas behind the separation in very general terms.
- *Why:* to make it easier to extend these ideas (and their advantages) to education.

2. Original Approach: Full Cognition

- *Original idea:* a good scientist (priest, witch, etc.) can predict everything.
- *Example:* ask oracles whether to start a war.
- *Example:* an Egyptian army marching towards an enemy could stop if the scarab beetles behave wrongly.
- *Example:* astronomer Ticho Brahe (16 cent.) was tasked to predict the fate of individuals – by horoscopes.
- *Another side of the coin:* how did they build cathedrals?
  - *idea:* we start building ten cathedrals, nine collapse, one remains standing for centuries;
  - *explanation:* God is punishing us for our sins.

3. Changes

- *Reminder:* two approaches:
  - everything is pre-determined, and
  - everything is determined by the God.
- *In both cases:* feeling that not much we can do.
- *This made sense:* in Dark Ages, when not much progress was made.
- *Industrial revolution:* changes everything by showing that rapid progress is possible.
- *Empirical fact:*
  - some things can be predicted (e.g., wind causes waves);
  - some things cannot be predicted (e.g., shapes of the waves).

4. From Full Cognition to Laplace Determinism

- *Empirical fact* (reminder):
  - some things can be predicted (e.g., waves);
  - some things cannot be predicted (e.g., their shapes).
- *Two consequences:*
  - notion of *randomness* (impossibility to predict);
  - idea of *Laplace determinism:* once we know the current state, we can predict the future.
- *In the past:* if you want to build a cathedral, just try building it.
- *New methodology:*
  - first, we need to know how things change (*science*);
  - then, we need to use this knowledge to design new things and processes (*engineering*).

5. Science and Engineering: Important Difference

- *Science* explains how the world changes.
- *Engineering* explains how to change the world the way we want it to change.
- *Karl Marx:* one of the first to understand the difference – and to apply it to social sciences as well.
- *Problem:* this separation is not well understood by the public.
- *Result:* engineering profession is not as respected.
- *Example:* a computer or a cell phone are engineering achievements.
- *However:* the small size of a cell phone is possible since we have science of antenna propagation.
- *Example:* atomic bomb was mostly engineering, but science was also needed (e.g., in isotopes separation).

6. Science and Engineering: Why We Need Both

- *What American kids are taught:* “scientific method”:
  - we formulate a hypothesis;
  - we test it.
- *Classical example:*
  - Edison tested hundreds of substances, and
  - found that Tungsten (Wolfram) works best.
- *What was it:* blind exhaustive search.
- *It was possible:* to find a material from hundreds possible.
- *It is not possible:* to find one of trillions of shapes of a cell phone antenna (or a medicine).
- *What is needed:* first, a scientific theory to predict the effect of different shapes (or different medicines).

7. Science and Engineering: Why We Need Both

- *At first glance:* we want to solve practical problems, let us do practical science.
- *Historical examples* of such short-sightedness:
  - Napoleon refused to finance a silly thing called steamship;
  - Stalin refused to finance a silly thing called atomic bomb;
  - Hitler prohibited working on a silly project called a ballistic missile.
- *After the successes:* the pendulum swung the other way:
  - V. Fock and L. Landau released from Gulag;
  - A. Sakharov ("Vasia") allowed to play ping-pong at work.

8. From Anecdotes to a Serious Analysis

- *What we have:*
  - results y_i or using designs x_i, $i = 1, \ldots, n$;
  - desired results $y'_1, \ldots, y'_m$.
- *What we want:* designs x'_j that lead to results y'_j.
- *Technical example:*
  - we know electromagnetic (EM) fields y_i generated by different antenna shapes x_i;
  - we need shapes x'_j for cell-phone EM fields y'_j.
- *Pedagogical example:*
  - we know the results y_i of applying different teaching strategies x_i to different students;
  - we need to find teaching strategies x'_j to achieve desired results y'_j for our students.

9. Why Separation into Science and Engineering

- *What we have* (reminder):
  - results y_i or using designs x_i, $i = 1, \ldots, n$;
  - desired results $y'_1, \ldots, y'_m$.
- *What we want:* designs x'_j that lead to results y'_j.
- *Problem:* we have a huge amount of data.
- *Solution:* separate the problem into steps so that we only process *some* data on each step:
  - first, we use x_i and y_i to find a relation $f(x)$ for which $f(x_i) = y_i$ (*science*);
  - then, for each $j = 1, \ldots, m$, knowing $f(x)$ and y'_j, we find x'_j for which $f(x'_j) = y'_j$ (*engineering*).
- In this way, we only process some of the data at the same time: the traditional divide-and-conquer idea.

10. Beyond Separation into Science and Engineering

- *Remaining problem:* on the science stage, we still need to process all pairs (x_i, y_i).
- *Natural solution:*
  - separate pairs into clusters (e.g., with similar x_i);
  - find $f(x)$ for each cluster; and
  - combine these "local" relations into a global one.
- *Similarity in physical terms:* $x_i \sim x_k$ if a simple transformation turns x_i into x_j.
- *In this case:* the goal is to find what transformation turns y_i into y_j.
- *Name of this approach:* symmetries.

11. Symmetries: Example

- *Problem:* find a period T of a pendulum of length L on a planet with free fall acceleration g.
- *Symmetry:* if we change a unit of length to a one λ times smaller, we get $L' = \lambda \cdot L$; e.g., 1.7 m = 170 cm.
- *Symmetry:* if we change a unit of time to a one μ times smaller, we get $T' = \mu \cdot T$.
- Under these transformations, $g \to g' = \lambda \cdot \mu^{-2} \cdot g$.
- *Idea:* find a function $f(L, g)$ for which $T = f(L, g)$ implies $T' = f(L', g')$, i.e., $f(\lambda \cdot L, \lambda \cdot \mu^{-2} \cdot g) = \mu \cdot f(L, g)$.
- *Solution:* by taking λ and μ so that $\lambda \cdot L = 1$ and $\lambda \cdot \mu^{-2} \cdot g = 1$, we get $f(L, g) = \text{const} \cdot \sqrt{L/g}$.
- *Interesting:* we did not use any differential equations.
- *In modern physics:* new theories come in term of symmetries, not diff. equations (starting with quarks).

12. Other Types of Clustering

- *What we did:* clustering by values x_i.
- *More general case:* clustering by the whole pairs (x_i, y_i).
- *One possibility:* cluster by similarity between x_i and y_i.
- *Example:* conservation laws – e.g., states x_i and y_i have the same energy.
- *Interesting:* from the mathematical viewpoint,
  - symmetries are equivalent to
  - conservation laws (the famous Emmy Noether's theorem).
- *Speculative idea:* maybe similar techniques can be used in education research?

13. Conclusion

- There is a clear distinction between:
  - *science* that analyzes how things are, and
  - *engineering* that analyzes how to change things.
- This distinction has been practically successful.
- This success can be reasonably convincingly explained:
  - this distinction divided the original hard problem
  - into several simpler problems.
- It is therefore desirable to promote a similar distinction in education.