# Defining engineers: How Engineers think about the world

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## Motivation for this essay

*It is not what engineers do, but how they think about the world that makes them different.*

Since this essay is written by a chemical engineer and is intended to help students or prospective students understand and appreciate engineering, I make the assumption that “different is better”.

## Summary

A person who calls herself a *Chemical Engineer* is expected to have a definable set of characteristics about how she views and interacts with the world as an engineer and a requisite “tool chest” (of analytical and mathematical skills) to use in this process. The intention of this essay is identify and explain this set of characteristics and give some insight into how engineers think. Students who are studying or wish to study *engineering*, need to be made aware of what it means to be an engineer and how each aspect of their education contributes to this outcome. I hope that this essay will help them to understand what they are trying to become.

## Overall traits of engineers

Engineers are more than middle-aged men who, when talking to non engineers about a particular device, will use the entire 8 character alpha-numerical code that their company uses to designate said device. As part of an overall definition, I suggest that *engineers understand how to use techniques of engineering analysis to design (i. e. synthesize) working devices and processes even though they have an imperfect understanding of important physical, chemical or biological* *issues.* Vincenti[i] (1990) gives several examples from aeronautical engineering where his view is that engineering is a battle against uncertainty. This imperfect understanding can be caused by too little time and or money to attain it, or because it is not attainable given the current level of pure and applied science. *Furthermore engineers operate under constraints caused by a need to produce a product or service that is timely, competitive, reliable, and consistent with the philosophy and within the financial means of their company.* Engineers are result driven and the detail of an engineering solution for a needed product, process or service is always determined by balancing competing effects to attain an answer that is optimal subject to the imposed constraints. These ideas lead to an example that I often work into my undergraduate classes. A mathematician is expected to produce the "correct" answer, which for a real problem means a number. A scientist will test nature and produce a number and its expected accuracy. An engineer needs to get the number (by any available means), its reliability or accuracy and then is expected to provide an opinion or judgment that will enable a device or process to be constructed.

## Engineering tools and approaches

In this section, examples of specific tools and approaches used by engineers are outlined. The discussion that is included is intended primarily to inform students who may read this.

Chemical engineers, perhaps because stoichiometry and thermodynamics are the usually the first two chemical engineering courses, verify that the **basic conservation laws** are satisfied. Unfortunately, I have regularly found that while students usually implement conservation laws in written problems, they often attempt to characterize laboratory experiments without regard to conservation laws. Fortunately, they seldom do it a second time! I think that their errors are not from lack of understanding of momentum, mass and energy conservation. They appear to arise

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[i] Walter G. Vincenti (1990) What Engineers know and how they know it, Johns Hopkins Press.

because routine translation of basic concepts into practice takes some time to develop. There is an interesting historical note worth mentioning about how these conservation laws are generally applied by engineers. Vincenti (1990) discusses the development of the control volume approach, which he attributes largely to Prandtl, and emphasizes that its use has been almost exclusively by engineers because of their need to understand specific devices or processes. In chemical engineering there has been increased use of solutions to the differential conservation equations, perhaps motivated by the publication of the seminal text, *Transport Phenomena*[ii] and certainly aided by improvements in computer hardware and numerical techniques. A counter argument to those who do not value the mathematical sophistication of current graduates, is the current practice of scaling up from bench to process without the one or two intermediate size levels that used to be common. This is possible because solutions to the governing equations and relations derived from them are (potentially) valid for all size scales.

With some notable exceptions (e.g., air flow over airplanes), the conservation laws cannot be solved in sufficiently detailed form to provide complete design information. This can either be because there is uncertainty about the constitutive relations (e.g., stress - strain relation for a polymer melt or P, V, T relation for a supercritical mixture) or because important phenomena occur over too broad a range of time and space scales to allow a useful exact solution. In these situations engineers use appropriate approximate procedures that are generally obtained from **dimensional analysis** combined with **experiments** based on systematic variation of the governing parameters. It should be emphasized that the dimensionless groups that result from dimensional analysis are typically *ratios* of important effects. For example if dimensional analysis is applied to the problem of a single fluid flowing in a circular pipe the result is the definition of two dimensionless groups, the *friction factor* and the *Reynolds number*. As with all situations when dimensional analysis is correctly applied, these groups are ratios of important competing or

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[ii] R. B. Bird, W. E. Stewart, E. N. Lightfoot, Transport Phenomena, Wiley, 1960.

complementing effects. For example the Reynolds number is the ratio of the inertial to viscous forces in a flowing fluid and its value defines much about the physical nature of the flow. A plot of friction factor versus Reynolds number for single phase flow in a smooth pipe is a single universal relation even when all of the individual variables (e.g., density, viscosity, fluid velocity, pipe diameter) are varied. Thus once this single relation is defined by experiments, it provides accurate predictions of pressure drop for laminar or turbulent pipe flow even though many important details of turbulent flow are not yet understood. Furthermore, data taken in the laminar region agree exactly with rigorous theory obtained by solution of the basic conservation law (momentum). It is interesting that the even more complex problem of flow in a packed bed can be addressed using an analogous relation, the Ergun equation. However, if two fluid phases are present in either a pipe or a packed bed, the number of dimensionless groups is too large and simple parameter variation does not yield useful procedures -- at least ones that can be used with much confidence. Students are all too ready to plug and chug using familiar formulas. If they need a heat transfer coefficient for pipe flow, they will calculate away with Dittus-Boelter or the like. However if phase change is occurring, two things usually occur both of which are bad. Many of them get stuck -- not realizing that such correlations should exist and they should be able to find them. Others take the even more egregious path of using Dittus-Boelter anyway. Fortunately by the time that they graduate, most students know where to look for correlations and constitutive relations and that they need to make sure of the range of validity.

To help understand complicated phenomena or complex devices or processes, engineers look first for the forest before trying to get species names for the trees. Furthermore, they get variety names and determine gender only if absolutely needed. In the ultimate simplification, most chemical processes look like: Reactor -- Separator. This approach leads to the use of the infamous (at least to younger students) **simplifying assumptions**. A favorite joke of Sophomore and Junior chemical engineers relates the escapades of a chemist, a physicist and a chemical engineer trapped in a raft in the ocean with plenty of canned nourishment and no can opener! After the chemist tries to corrode a can open and the physicist tries to burn a hole through on by focusing sunlight with his glasses, the chemical engineer proudly states: "Assume the can is open!!" The ability, as John Prausnitz[iii] states: "... to distinguish between what is essential and what is incidental.", may take many years to develop. However, it is imperative that students understand the need for and utility of this philosophy. A (serious) example that I use in class demonstrates that simplifying assumptions are possible when an effect can be neglected not because it is small per se, but because it is subordinate to a dominant effect. The example involves curveballs and knuckleballs as thrown by competent major league pitchers. In the case of a good curveball, imperfections in the ball and air currents do not significantly affect the trajectory. However for a knuckleball, which has no effective spin stabilization, air currents and ball imperfections are the reasons that the ball usually follows an erratic trajectory that makes it difficult for the batter to hit.

To get rational simplifying assumptions, engineers often find a **parameter** that can be **taken to a limit** -- either large or small. This idea can be used for something as simple as figuring out how heat of vaporization or interfacial tension change with temperature. A second implementation could be a recycle reactor where the recycle rate would allow variation from CSTR to plug flow behavior. It may not be possible to solve all intermediate cases, but getting information in the two limits may be sufficient. If a fundamental parameter is taken to its limit then this approach is the physical analog to perturbation theory. Of course the limit could be singular (e.g., Reynolds number --> ∞) which causes problems. However if the limit is regular, (e.g., Reynolds number -->0), there is a firm basis for correlations of the form $Sh = 2 + \beta\, Re_{\mathrm{p}}$, which in this case allows determination of the mass transfer coefficient from a particle in a stirred fluid. This idea generalizes well to other fields of endeavor although it can lead to absurdity. For example it is useful examine the limiting effect of increasing or decreasing interest rates if we believe too much in the tonic of small changes.

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[iii] from: John M. Prausnitz (1969) Molecular Thermodynamics of Fluid - Phase Equilibria, Prentice-Hall p.182.

A final tool that I include in this section is perhaps is somewhat subtler than the others and may not understood by all graduating seniors. This is appreciation of the difference between processes in which **rate** of approach to equilibrium can be used as a basis for design and those in which all the pertinent rates are sufficiently fast that the process is effectively governed by the **extent** of **equilibrium**. Furthermore that there is an inherent tradeoff between the rate of a process and its degree of thermodynamic efficiency that often leads to capital equipment versus operating cost tradeoff. An example of rate versus equilibrium based design is packed versus tray contacting columns. Staged columns are designed by assuming that two fluid streams attain equilibrium on every stage. Conversely, determination of the height of packed columns involves a product of an integral of the driving force (distance from equilibrium in chemical potential) and a group that contains the mass transfer coefficient and effective residence time. The two fluid streams are not supposed to be in equilibrium anywhere. If a packed device is designed to have a larger integral driving force, the rate will be larger and the device correspondingly smaller (lower capital costs) but the thermodynamic efficiency will be lower (higher operating costs). The same tradeoff exists in staged devices. As a column is operated closer to minimum reflux, the average difference from equilibrium of streams entering stages decreases, requiring a larger number of stages but lower heat requirements.

## Combining the traits to make an *Engineer*

Simple possession of the individual tools and talents (and perhaps others that I have omitted) does not assure that students can use them to produce the devices, processes and services that comprise the products of engineering practice. To really be an engineer, a student must understand how to bring together knowledge of previously solved (by her or others) problems and understanding of the current *need* to **synthesize** new solutions. A new solution might be quite complex but an engineer understands how it is really comprised of simple, well understood pieces. Development of synthesis as a skill requires practice throughout the engineering curriculum on “open ended” problems (example and homework problems that do not have completely defined single answer solutions). If students are given just one big open-ended project that has societal significance and requires economic analysis in their senior year, most of them are not going to gain much understanding of synthesis or that all designs require balancing competing, sometimes not well understood effects. In a previous publication[iv], I mention that typical students (i.e., students in the middle of the class by grade average) seemed to acquire a better overall feel for the “balancing” that is the essence of design, if problems were greatly simplified leaving only the essential components.

## Using these traits outside of engineering

An additional benefit of defining the *thinking* traits of engineers is that it will make these traits more exportable. Engineers have an excellent record of success in the business world. Certainly part of this is because they “think like engineers” in the solution of (at least some) business problems. Since these engineering traits are generally useful, it might be wise for engineering faculty to provide opportunities and examples of the use of engineering traits in other fields (just as we provide engineering examples). Because many students who are not engineers could benefit from our view of the world, it could be good for society as a whole (and perhaps personally profitable) if engineering faculty find ways to communicate our way of thinking to students outside of engineering. In the Appendix, I give a possible outline for such a course.

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[iv] M. J. McCready, "An alternative to the process design course", Chemical Engineering Education, 23, p 82-85, 1989.

# Appendix:

## Course outline for demonstrating how engineers think to non-engineers.

### Basic premise

Engineering is RESULT driven and the primary goal is always the same: Find the OPTIMAL solution to a problem. Optimal is usually modified or defined in the context of (for example):

1. Imperfect understanding of important physical/chemical/biological/ issues (limited time and money to find this understanding)
2. Financial -- based on not necessarily well-defined markets or other social issues
3. Ability to <u>actually produce</u> the item or service as needed and promised
4. Consistent with the philosophy and practice of the client or company.

Topics that if appropriately linked together demonstrate how engineers think:

(1) Building up complex problems from simple pieces (synthesis)
(2) Testing correctness of results by matching the dimensions of the variables involved or taking variables to their limits
(3) Developing general relations by forming dimensionless groups and showing the way complex structures can be understood in terms of these dimensionless groups
(4) Experiment or testing design to find the important cause/effect, (i.e. to distinguish important from incidental) or to produce a statistically valid outcome
(5) Use of numerical simulation as an experimental tool to probe issues of a problem
(6) The idea that many finished items can be designed based almost completely on numerical solutions of fundamental equations.
(7) Showing that in real problems competing effects are or must be balanced and that this leads to the need for an optimal solution.
(8) The inherent difference between situations that are governed by a true equilibrium versus problems that are rate processes and must be controlled by how fast something occurs