DEVELOPING CREATIVITY AND INNOVATION IN ENGINEERING AND SCIENCE

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In this talk I discuss a range of topics on developing creativity and innovation in engineering and science: the constraints on creativity and innovation such as the necessity of a fitting into the realities of the physical world; necessary personal qualities; getting a good idea in engineering and science; the art of obsession; the technology you use; and the technology of the future.

1. Creativity and Innovation in Engineering and Science

1.1. *Creativity*

Creativity is sought everywhere: in the arts, entertainment, business, mathematics, engineering, medicine, the social sciences, and the physical sciences. Common elements of creativity are originality and imagination. Creativity is intertwined with the freedom to design, to invent and to dream. In engineering and science, however, creativity is useful only if it fits into the realities of the physical world.

1.2. *Examples of Constraints on Creativity and Innovation*

A creative idea in science or engineering must conform to the law of conservation of energy (including the mass energy mc^2). An inventor that thinks that she or he knows how to violate the conservation of energy will have to disprove a vast amount of laboratory measurements and accepted theory.

Figure 1 shows a traditional design for a perpetual motion machine, a rotating wheel with moving weights that seem to always give the wheel a non-zero torque. A direct dynamical analysis of the forces is tedious, therefore physicists and engineers simply use conservation of energy to negate the scheme, but this does not convince perpetual motion zealots who vary

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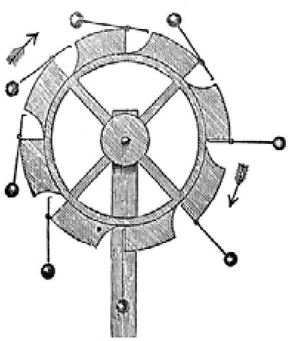

Fig. 1. A traditional proposal for a perpetual motion machine.

the design. At present many perpetual motion seekers are thinking about obtaining energy from the quantum mechanical fluctuations of the vacuum. This is a sophisticated proposal and negating it is complicated, perhaps at some deeper level the proposal has validity, but a radical change in our physics theory and new experiments are required before one should talk about building a machine to extract energy from the vacuum.

A creative idea in science or engineering must conform to our present knowledge of the nature of matter as shown in Fig. 2, unless we invent or find a new form of matter. Of course we have created new structures out of the known forms of matter such as nanotubes and layered materials.

1.3. *Observations and Rules of Thumb*

If your idea is in an area where the basic science or mathematics is not known, begin by paying attention to the known observations and rules of thumb in that area. Keep in mind, however, that observations and rules of thumb may be wrong. Remember when doctors thought that stomach ulcers were caused by stress or spicy food, now it is known that most ulcers are caused by bacterial infection.

1.4. *Practicality and Feasibility Constraints*

Creativity in science, engineering and computer science is constrained by feasibility and practicality. Consider the work in the US on a nuclear reactor powered airplane in the 1950's. Before the development of intercontinental missiles there was a desire to build a bomber that could fly around the world and perhaps even keep circling [1]. There were three severe problems faced

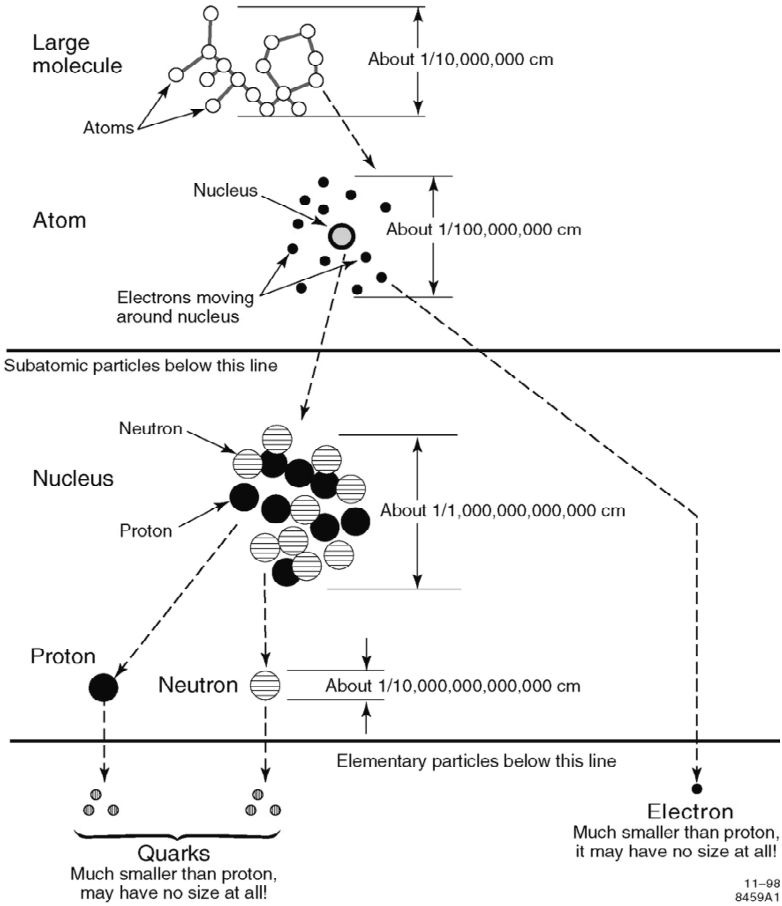

Fig. 2. All objects are made of the ordinary matter outlined here. There are other known types of matter such as unstable quarks and leptons, force carrying particles such as the Z^0, and dark matter. But we do not know how to make objects of these particles.

by the designers: the weight of the reactor and the shielding, the shielding of the crew from the reactor radiation, and the contamination of an area if the plane crashes. Tests went as far as connecting a nuclear reactor to an engine. But the plane was never built. This idea violated the constraint of feasibility.

Since the maturation of automobile technology and powered aircraft technology, inventors have dreamed of a flying car, a vehicle used by the public that could be driven on the road or flown. The vehicle would have easy convertibility between the two modes, Fig. 4. There have been a few

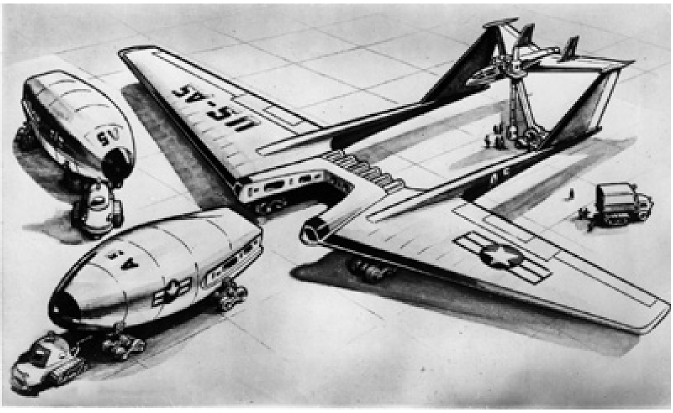

Fig. 3. An artist's conception of a nuclear reactor powered airplane. The crew's cabin would be in the rear, far from the reactor in the front.

temporary successes but the concept does not meet the constraint of practicality. How is the airspace to be regulated? Where are the wings when the vehicle is used as an automobile. What is the cost of purchase and maintenance?

2. Necessary Personal Qualities for Creativity in Engineering and Science

2.1. *Be Competent in Mathematics*

You don't have to be a mathematical genius. While there are positions in scientific and technical fields that don't require much mathematics, you should be competent in mathematics so that you can understand new developments.

2.2. *Visualization*

In engineering and scientific work it is crucial to be able to visualize how the work can be accomplished. The intended work might be the invention of a mechanical or electronic device, the synthesis of a complicated molecule, the design of an experiment to evaluate the efficacy of a new drug, or the full modeling of how proteins fold and unfold.

Different kinds of work require different kinds of visualization. Spread sheets or flow charts may work best in some cases. Drawings might be more suitable in others. Whatever the project, the value of visualization is

Ted Hall's original idea in mating an automobile to an airplane was to develop a design that paratroops and commandos could use.

Drive Right Up

With its 30-foot wing and its tail removed, the flying auto looks pretty much like other cars on a highway. Its

A FLYING automobile with a 130-hp. Franklin engine cruises at 110 m.p.h. in the air and travels 60 m.p.h. on the road. Those speeds were set by the first model of a design by Ted Hall, aviation engineer. Portable Products Corp., Garland, Tex., is considering the possibilities of producing it.

The "roadable" plane has detachable propeller, wing, booms, and tail. The forward end of the engine crankshaft turns the prop, while a shaft extends aft from the engine into a conventional automobile transmission and differential. Power goes both to propeller and rear wheels for the take-off.

Hall's three-wheel, "roadable" airplane seats only two, but has ample luggage space in the rear. Rear wheels are on shock struts.

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Fig. 4. A typical popular magazine forecast of a flying car.

in finding the best way to proceed while avoiding mistakes and perhaps even finding alternative solutions or good related ideas. Do not go into engineering or science if you do not have a basic ability to visualize. Visualization is crucial for creativity in engineering and science!

2.3. *Imagination*

Imagination is another crucial ability required to be creative in engineering and science — imagination with respect for the constraints I have talked about: known physical laws, correct observation and experimentation, feasibility, practicality. Begin with the far reaches of your imagination at the science fiction level, then gradually apply these constraints. Figure 5 shows the change from Jules Verne's science fiction space vehicle to the space shuttle.

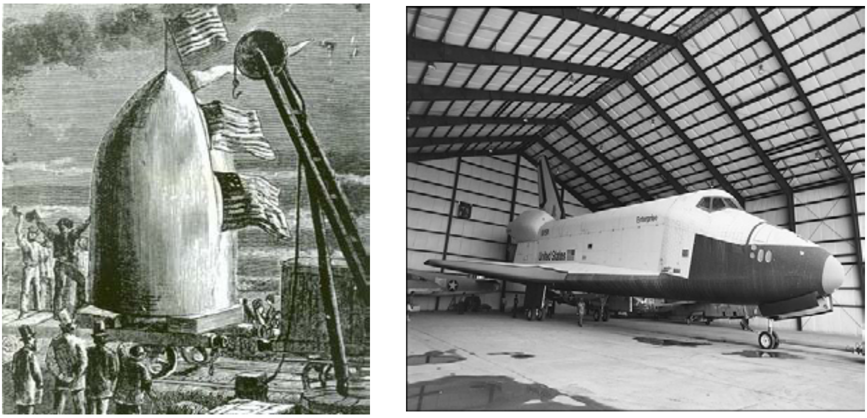

Fig. 5. The change from a science fiction space vehicle to the Enterprise space shuttle.

2.4. *Evaluate Your Laboratory Skills*

Evaluate the extent of your hands-on skills and laboratory skills. Are you good at working with tools, at building equipment, at running equipment — electronics, microscopes, telescopes...? This is my strength. I am an experimenter in physics because I like to work on equipment, am mechanically handy and get great pleasure when an experiment works. But hands-on skills do not have to be your strength. Isadore Rabi, my doctoral research supervisor at Columbia University in the 1950's, had no laboratory skills. Yet Rabi won a Nobel Prize for advancing experimental atomic physics. When choosing what to work on in engineering and science, honestly evaluate the extent of your hands-on and laboratory skills.

3. Getting a Good Idea in Engineering and Science

3.1. *Personality and Temperament*

You must take into account your personality and temperament when choosing a technical field, or particular field of science. Be yourself. Creative scientists and engineers have many different types of personalities.

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3.2. *It is Much Easier to Get Bad Ideas than Good Ideas*

In science and engineering for every good idea expect five or ten or twenty wrong ideas, or useless ideas, or obsolete ideas. Consider some of the following obsolete, bad ideas:

- The phlogiston model of combustion.
- Lamarckian evolution.
- A physical electromagnetic ether.
- Steam powered automobiles that can be competitive with internal combustion automobiles.

There are other ideas that appear to be wrong but are still pursued:

- Cold fusion.
- Using zero point energy from fluctuations of the vacuum.
- Telepathy.

3.3. *Great Engineers and Scientists Have Bad Ideas as well as Good Ideas*

Nikola Tesla was a pioneer and inventor in electrical technology. He was one of the first to understand alternating current phenomena and its use. He was one of the first to demonstrate the feasibility of long distance wireless, indeed in this field he is the equal of Marconi. But he also thought he could use the same wireless transmitting tower, Fig. 6, to transmit efficiently, large amounts of low frequency power to an antenna very far away. At the radio frequencies used by Tesla this was not possible because the power spreads out rapidly. Of course, substantial amounts of power can be transmitted at high frequencies using microwave beams. I don't understand how Tesla, who understood radio theory so well and could visualize alternating current phase diagrams in his head, could be confused here.

3.4. *Reduce the Frequency of Bad Ideas*

There are several rules for reducing the frequency of your bad ides. Make sure that you understand the physical laws and the neighboring technology relevant to your new idea. Colleagues, the literature, and the Web can be of help. Sometimes you have to keep going until *you* are the expert on the idea and *you* discover the show-stopper! Try to avoid the "dam the torpedoes, full speed ahead" state of mind. Several times I have rushed into a project even though it didn't feel quite right, just hoping that it would work out in the end. It never did work out.

Fig. 6. A tower used by Tesla to transmit wireless signals. He also hoped to use such a tower to transmit large amounts of electrical power over long distances.

3.5. *Sorting Out Good and Bad Ideas*

On the other hand you may turn a bad idea into a good idea — don't kill the bad idea prematurely. A bad idea can evolve into a good idea. This evolution into a good idea can be a short process, like turning a bug into a feature, to quote my colleague Eric Lee. Or the evolution from bad to good can be long with many intermediary steps. It is rare for the complete development of a good idea to occur quickly. Be prepared for a winding road of research, development and prototyping or for a maze with many wrong turns.

3.6. *Can Creativity and Innovation Skills in Engineering and Science Be Taught in the Classroom?*

I believe the pressure of reality is important — a product *must* be improved or an experiment must work or a more efficient computer algorithm is *needed*. I don't think these skills can be taught in the classroom. For a contrary view see Ref. 2.

3.7. *Helpful Hints*

Keep your eyes and ears open by scanning the literature, usually through the internet these days. Also eat lunch with colleagues, don't eat at your desk. Avoid the "not invented here" prejudice. If you find an available technology that is superior to your own, use it!

You can learn from many people with different talents and different technical specialties. Five years ago we wanted to make a colloidal solution of powdered meteorite, my academic friends in colloid science were of little help, they knew a great deal about the theory and behavior of colloidal solutions of pure substances. But our meteoritic material consisted of a mixture of minerals such as silicates plus small metallic nodules. We learned how to make a colloidal solution of powered meteorite from an engineer who was a specialist in the lubrication of automobile engines. One of the functions of engine oil is to suspend small particles that come from engine wear and incomplete combustion.

3.8. *Limit Your Working Hours*

These days there is pressure in engineering and science to work very long hours, a "24/7" work-week. But creativity and innovation require relaxation time and non-technical activities.

3.9. *Luck*

The importance of Good Luck is overrated for discovery and innovation in engineering. For a contrary view see Ref. 3.

But it is important to avoid Bad Luck. The basic avoidance principle is the same as being careful when crossing a freeway. In engineering and science most bad luck is caused by mistakes in calculations, design, measurements, or experiments.

4. Colleagues

In the modern world the highly productive solitary engineer or scientist is rare. Find colleagues who are smarter than you and know more. I always look for such colleagues. The obvious advantage is that she or he may be able to solve the problem that has produced a dead end in your work. But more importantly, smart and knowledgeable colleagues can save you a lot of time!

You don't have to be a fast thinker or a fast talker. In fact, it is best to avoid having such people as colleagues.

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5. Obsession

5.1. *Obsession is Important When You Have a Good Computing, Engineering, or Scientific Idea*

When you are imagining and visualizing an idea that you expect to be fruitful it is important to be obsessed with the idea. Think about the idea as much as possible — perhaps even to the extent of neglecting boyfriends, girlfriends, children or spouses. Obsession, immersing yourself in the problem, will enable you to focus and thoroughly explore all the aspects of the idea: what has been done on related ideas, compatibility with physical laws and mathematics and logic, feasibility, practicality, extensions, and variations.

Obsession involving an entire field often leads to great new technology. Serious efforts to build a powered, heavier-than-air airplane occupied decades before the Wright brothers flew in 1903, Fig. 7. They were the first to make a controlled flight using design principles that are the foundation of present airplane design.

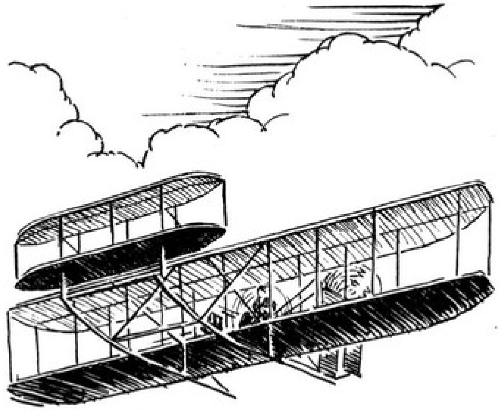

Fig. 7. An early airplane built by the Wright brothers and the brothers themselves: scientists, inventors, and entrepreneurs.

5.2. *Ending Obsession*

But, if in the course of the work you find that you run out of money, or someone else has a better idea, or your idea has a serious flaw — give up the obsession and move on!

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An entire field can also be involved in a hopeless obsession. A good example is the concept of using a rigid, lighter-than-air dirigible to complete with airplanes. This was exciting technology in the early decades of the twentieth century. But almost all dirigibles, whether commercial or military, crashed or were dismantled within a decade of their construction. The building of commercial or large military dirigibles ended in 1938 when the Hindenburg zeppelin exploded and crashed in New Jersey, Fig. 8. The obsession was over.

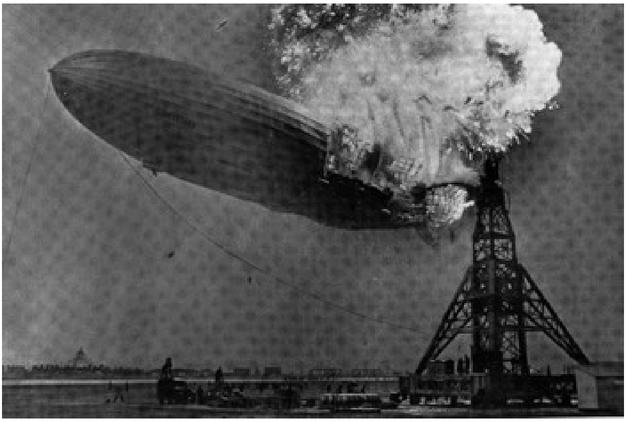

Fig. 8. In New Jersey in1938, during the process of mooring the Hindenburg zeppelin to the mast, the Hindenburg exploded and burned. The Hindenburg used hydrogen for lift. There are many explanations of the cause of the explosion.

5.3. *Ambiguous Obsession — Power from Controlled Fusion*

Since the 1950's a substantial scientific and engineering community has been working on using controlled nuclear fusion to produce power. The physics and engineering is understood in outline. There is no violation of any known laws of nature. There are several reasons for the long gestation period. The plasma physics is very complicated and details may not yet be understood, even prototype apparatus are enormous and expensive. There are severe engineering materials problems to be solved.

Yet the controlled fusion scientific and engineering community believes that it is feasible to build such a power plant. The question is practicality. How much will it cost to build and operate a fusion power plant? I think the fusion powder community is obsessed. It may be a good obsession that will lead to final success, or it may be an obsession that should be ended.

6. The Technology You Use

You must be interested in — perhaps even enchanted by — some of the technology, software, or mathematics you use. Then the bad days when the project or the research is stalled or moves backwards are not so bad, at least you have enjoyed the technology.

My 1955 Ph.D. thesis [4] made use of the atomic beam resonance apparatus of Fig. 9 for measuring the nuclear quadrupole moment of sodium.

The apparatus was beautiful — a shining brass vacuum vessel with a glass McLeod vacuum gauge filled with mercury. The current for the beam deflecting magnets came from surplus submarine batteries that were recharged every night from an ac-dc motor generator set. The sodium beam was produced by a pinhole oven that could produce a beam for about eight hours. I loved the technology and had myself built the smaller parts. But if the oven clogged I had to stop the experiment, clean and refill the oven, recharge the submarine batteries, *that was a bad day.*

Another advantage of being enchanted by the technology, programming, or mathematics that you work with is that you will be more likely to think of improvements and variations.

You should be fond of the technology, mathematics, or programs that you use, but not so much in love that you are blind to the possibility that there may be a better way.

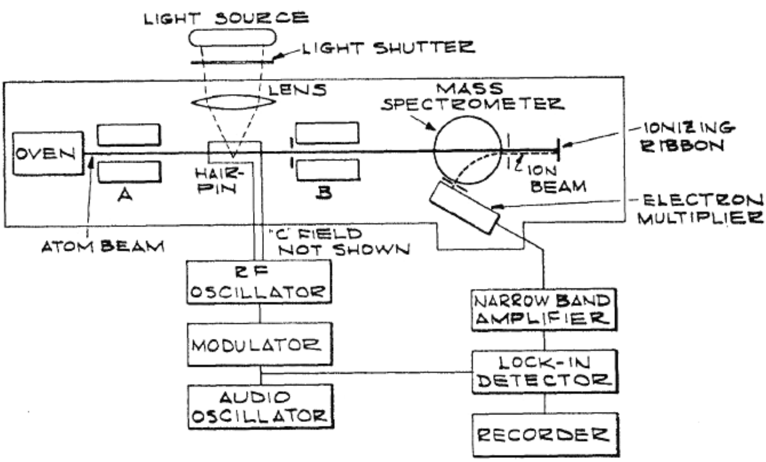

Fig. 9. A schematic of the apparatus I used in my 1955 Ph.D. thesis. I drew this, in 1955 there were no computer drawing programs.

7. The Technology of the Future — Replacement of Technologies

It is often impossible to predict the future of a technology. Some technologies are replaced again and again by new technologies serving the same function. An example is sound reproduction.

- Invented in 1890's: Gramophone and phonograph mechanical inscription of a physical trace of sound on a disc or a cylinder with mechanical reproduction.
- Introduced in 1920's: Electrical amplification used for mechanical inscription and sound reproduction. Gradually replaced purely mechanical system. Cylinders no longer in general use.
- Introduced in 1950's: Long playing records.
- Introduced in 1960's: Radical change in technology by recording on magnetic tape, cassette format dominant.
- Introduced in 1980's: Another radical change in technology — development of the Compact Disc with digital recording. Until then all widely used systems for sound reproduction were analog.
- Present: Prevalent use of digital sound recording on magnetic hard drives and flash memories.

8. The Technology of the Future — Incremental Improvements

Some technologies persist through incremental improvements. A good example is the reciprocating internal gasoline engine, developed in practical form largely in Germany in the last few decades of the nineteenth century. Many efforts have been made to replace the use of internal gasoline engines in automobiles and small trucks; for example the Wankle rotary engine has been tried commercially. But the reciprocating internal gasoline engine is continually improved with the use of new auxiliary technologies such as computer control, Fig. 10.

9. The Technology of the Future — Some Promising Technologies Go Nowhere

Early in my technical career I learned that some promising technologies go nowhere. In 1950 I was a chemical engineer working in a radio tube factory of the U.S. General Electric Company. My boss had a special interest in developing very small radio tubes for use in portable radios and hearing aids. The smaller filaments used to heat the cathode would take less

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Fig. 10. The reciprocating internal combustion engine has a hundred year successful history.

power allowing a longer lasting battery. other tube companies had the same interest. My boss also pointed out that very small vacuum tubes would be an advantage in home radio sets because the time between turning on the set and hearing the sound would be shorter since the filament would heat up faster.

While we and other companies worked developing smaller vacuum tubes, the transistor was invented at Bell Laboratories in 1949 by John Bardeen, Walter Brattain, and William Shockley. The transistor age had arrived and the small vacuum tube was relegated to a few special uses, Fig. 11.

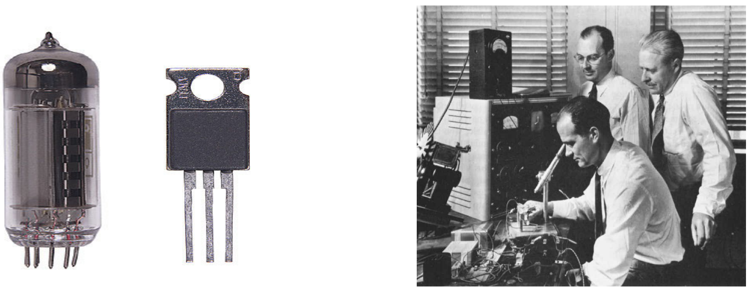

Fig. 11. On the left a small vacuum tube, in the center an early transistor, on the right the inventors of the transistor.

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