CONFLUENCE

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"I sell here, Sir, what all the world desires to have –POWER" Boulton to Boswell 1776

About six thousand years ago man invented the wheel. Soon after that he began to use pack animals and by 2500 BC animal drawn wheeled vehicles were being used for transportation. Boats also came early, probably because of the clues provided by floating logs and other river debris. Around 3000 BC sails were added to small boats. Water wheels date from around the time of Christ. Windmills were built in Persia around 650 AD and in Europe around 1200 AD. <u>No new source of power appeared until about 1700 AD</u>. The point to this is that for all but a few hundred of the last 6000 years, man has relied on muscle (human and animal), wind and water for power. It is interesting to ponder why.

In the same stretch of time, great civilizations appeared and disappeared. Wonderful buildings were erected. The pyramids date from around 2500 BC and the Parthenon was finished in 438 BC. Try to imagine how these enormous structures were built with nothing but muscle power. Liquor was distilled in Asia around 1475 BC. Great literature was written; Homer's *Iliad* and *Odyssey* around 925 BC, Thucydides *History of the Peloponesian War* around 400 BC. Exploration and wars expanded the Roman Empire to extend from the western coast of Spain to the northern tip of the Persian Gulf (over 3000 miles) and from northern Africa to the British Isles (about 1500 miles), roughly the size of the forty-eight states. Euclid's geometry has been taught since about 300 BC. Fifty or sixty years ago it was still an entrance requirement for many colleges. These comments focus mainly on Greek and Roman accomplishments, but later there were also great Arabic and Mayan civilizations. Greek science was disseminated first in Greek, then translated into Arabic and extended, but not until the Middle Ages was it translated into Latin. Arabic translations and Arabic science were critical to the Western European scientific

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revolution, which began toward the end of the Middle Ages. The oldest of the great universities came into existence around 1200 AD. The world did not want for demonstrations of intellect or great achievements or notable events.

The Renaissance (~1350-1600) saw evolutionary development of technology, but only two really striking high impact additions to Western Technology: gunpowder and printing. Printing produced a better record of the development of technology after about 1450. In particular two books dealing primarily with metallurgy, Biringuccio "Pirotechnia' (1540) and Agricola "De Re Metallica" (1556), were published in the sixteenth century. Agricola's book was the standard metallurgy reference for almost two centuries. In 1598 Phillip III of Spain offered a substantial prize and a lifetime pension, which were not successfully claimed, for the invention of an accurate way of determining longitude at sea. The seventeenth century saw a continuation and expansion of the sixteenth century trends. Coke was discovered setting the stage for using coal in the smelting of iron. Cornelius Drebbel built a successful human-powered submarine. His secret was producing oxygen from saltpeter (KNO_3). Torricelli (1608-47), Pascal (1623-62) and von Guericke (1602-86) advanced the understanding of atmospheric pressure and Papin (1647-1712?) first used steam to lift a piston and then condensed it to cause atmospheric pressure to force the piston down. Later he used steam to provide the power stroke. He did not, however, design a steam or atmospheric engine. Toward the end of the century Thomas Savery (?1650-1715, FRS) devised a way of using steam to pump water. The engine was demonstrated to the Royal Society in 1699. It was not strictly speaking an engine, but he was granted an incredibly broad patent for a "... new Invention of Raiseing of Water and occasioning motion of all sorts of Mill Work by the Impellent Force of Fire...". The breadth was unjustified and the invention was not a great success, Savery quit promoting the engine in 1705. As we will see, the breadth of the patent forced Newcomen into partnership with Savery. At the end of the seventeenth century there were still only three useful sources of power: muscle (human and animal), wind and water.

The Eighteenth Century--Steam Engine

[Kit-Kat Club 1700] In spite of the dependence on muscle, wind and water for power, an amazing variety of mechanical devices had been invented by the beginning of the eighteenth century. Clocks, textile machinery, mills, and some machine tools had been built. By modern standards all of these were primitive and many were commercial failures. The eighteenth century was characterized by a great deal of evolutionary development and a few striking, revolutionary inventions. In 1714 the British Parliament offered a 20,000 pound prize, for a clock sufficiently accurate to determine longitude at sea. This was the second prize offered for an accurate way of determining longitude at sea. Clocks of various kinds had existed for over 1700 years, but winning the prize required a huge improvement. John Harrison won the prize in 1765. The blast furnace, the use of coke rather than charcoal in smelting iron, rolling mills and many other improvements and innovations made iron and steel important commercial products. The famous "Iron Bridge" at Coalbrookdale was built in 1779. Boring cannon led eventually to boring machines that could produce accurate cylinders for steam engines. Wilkinson's little known boring mill had a profound effect on the development of prime movers. All of these were, however, essentially evolutionary rather than revolutionary. The landmark invention was the steam engine or more precisely the atmospheric engine.

The Newcomen (1663-1729) engine, which appeared on the scene in the early years of the eighteenth century, did not develop from earlier related devices. It was not the culmination of a series of improvements. It was totally new. Usher (p.347) describes it as follows: "The invention of the atmospheric engine in this form [the Newcomen engine] was the greatest single act of synthesis in the history of the steam engine." This statement is quite probably conservative. The engine operates as follows: Steam fills the cylinder enabling the excess weight on the pump end of the beam to tilt the beam and raise the piston. Cold water is sprayed into the cylinder to condense the steam and produce a partial vacuum. This was the unique feature of Newcomen's engine. Atmospheric pressure pushes the piston down returning it to its original position and raises the pump end of the beam. This sequence of events is repeated and cycles a pump, which raises water a distance equal to the stroke of the piston. Note that the work of lifting the water is done by atmospheric pressure rather than by the steam, thus the name, "atmospheric engine". The first successful engine of this type seems to have been installed in a mine near Dudley Castle in Staffordshire in 1712. But, there are no really good records.

This story has many interesting sidelights. One of these is that most of us were taught that James Watt (1736-1819) invented the steam engine. This myth probably developed in part because Newcomen left no written record of his work on the steam engine. All that is known to survive of his writing is a single letter to his wife. There is no known likeness of Newcomen. Further, he was an ironmonger, rather than a Fellow of the Royal Society, and an ironmonger could not possibly have made such a significant invention except by pure chance. Further, Newcomen could not patent his invention because, as noted earlier, Savery had obtained an unbelievably broad (master) patent, which was extended to 1733 and which really encompassed all heat engines.

All of these items contributed to Newcomen's obscurity. He was, however, indefatigable. Through a partnership with Savery, which was probably formed in 1705, he was able to build engines apparently to the profit of both. Unfortunately, early writers frequently referred to Newcomen engines as Savery or Savery-Newcomen engines, thus adding to Newcomen's obscurity. By the time of Savery's death in 1715 at least seven engines were working in England. A London syndicate obtained control of the patent in 1715. By the time the patent expired in 1733 many more engines, perhaps fifty, had been built. With the expiration of Savery's patent, engine building boomed, other builders began erecting engines, more engines were built in Europe and one was exported to the American colonies in 1753. A new source of power had finally arrived and this was a landmark.

We now have an idea what happened—Newcomen invented the atmospheric (steam) engine, which was the first really useful prime mover to supplement muscle, wind and water power. Why did it happen at the beginning of the eighteenth century and why in England? The answer is in my opinion, that there was a **confluence** [I had to get the word in somewhere], a coming together in time and space of a need, resources and a socio-economic environment favorable to using the resources to satisfy the need. In the case of the Newcomen engine, the need is fairly obvious. Mining in England had largely exhausted the shallow deposits of ores and coal forcing miners to resort to vertical shafts and deeper mines. Deep mines almost always suffer from water seepage and will flood if the water is not removed. This was well known. Agricola devotes a substantial section of "De Re Metallica" (1556) to removing water from mines using human, animal and water power. In English mines, however, the amount of water and the depth from which it had to be raised had come to exceed what could be done reasonably with human or animal power and often there was no water power at the mine heads. Windmills were not a viable option because the winds in England are too uncertain for mine pumping. Mine owners and operators were going bankrupt as a result of flooded mines. The first pumping engine developed about five horsepower, the equivalent of about 125 men or fifteen horses (a horse, interestingly, works at a rate of about one-third of a horsepower) working simultaneously, and required only a single attendant. A Newcomen engine could pump a mine dry and keep it dry at a high, but affordable, cost. Other sources of power could not. The performance of the engine was, however, unknown until the first one was installed in a mine. The first mine owner who installed a Newcomen engine committed a great act of faith.

The socio-economic environment was favorable. The landed gentry leased land for mining and consequently they had a vested interest in the success of the mines. Parliament had encouraged inventions for pumping water by granting patents for "water commanding engines" to at least three individuals, including Thomas Savery. The language of these patents is arcane at best, but the patent concept was directed towards insuring that inventors gained the fruits of their labor. On the other hand, some fellows of the Royal Society looked down on inventors who were not fellows and tended to deprecate their efforts and inventions. Passages from J.T. Desaguliers "A Course of Experimental Philosophy" are often quoted for their incorrect and deprecating comments about Newcomen's achievements.

Financing the experimental engines probably was not a problem. Newcomen was a reasonably prosperous ironmonger and, as were the ironmongers of his time, not only a merchant, but also an artisan. He probably made most of the parts for the experimental engines himself with e aid of an assistant who is often described as a plumber. Pumps were routinely made with cylinders up to about seven inches in diameter. Pump cylinders, at that time, were not very good, but they were surely adequate for Newcomen's experiments. Other components, except for the boiler, were relatively simple and easily produced in a modest workshop. Understanding the development of the concept is, however, a vexing issue. There are contemporary writings by Newcomen's associates that indicate that he did not know Savery until 1705 when he discovered that his patent was blocked by Savery's master patent. The works of Torricelli, Pascal and von Guericke were published in Latin, French or German and probably unknown to Newcomen. Papin, however, moved to England in 1675. Sometime between 1690 and 1695, Papin demonstrated a device that raised a piston by steam pressure, allowed the steam to condense and then used atmospheric pressure to force the piston down and raise a weight by means of an arrangement of a cord and pulleys. This was about when Newcomen started working on his pumping engine. He may have heard of Papin's demonstration, but nothing conclusively verifying or contradicting that thought has been found. My best opinion is that we do not know and probably never will know exactly how the concept developed.

Newcomen's engine was a start. Many improvements in the engine appeared, but the basic concept did not change until 1865 when James Watt had the brilliant idea of condensing the steam in a separate condenser rather than in the engine cylinder. This idea was patented in 1869 and roughly doubled the efficiency of the engine. Watt and others left a written record of his efforts and it is clear that the separate condenser was the product of rational analysis. The improved efficiency made the Watt engine practical in Cornwall where coal was very expensive. Watt also modified the engine to produced rotary motion and so made it useful to power factory machinery. Engines of this type were used to power Wilkinson's machine shop in 1783 and the Albion Mill at Blackfriars London in 1784. The floodgates were now open and the use of steam engines spread very rapidly. By 1800 there were about 500 Watt engines, averaging 15 or 16 horsepower, operating in England.

The Nineteenth Century

Reciprocating steam engines were the main source of steam power until roughly the end of the nineteenth century. More powerful, but larger, heavier and inevitably noisier, engines were built. Reciprocating steam engines powered electrical central stations beginning around 1880 and to follow the story we must turn very briefly to electricity.

In 1799 the only knowledge of electricity dealt with static electricity, that is phenomena similar to lightning, but on a smaller and more controlled scale. In 1800 Volta (from whose name volt is obviously derived) disclosed his invention an "electric pile" or what we would call a battery. With a battery one can produce sustained currents (current electricity), much the same sort of tame electricity we use, without much thought, in our homes, automobiles, factories and pretty much everywhere. Volta's battery was replicated and improved in many laboratories. With the ability to produce sustained currents, understanding of the fundamental laws governing electricity and magnetism developed very rapidly. This new understanding was exploited to make small demonstration devices, electro-mechanical generators, which converted a mechanical input into current electricity. By 1869 Gramme had developed and was manufacturing commercially useful electric generators. Arc lights were demonstrated and found practical for lighthouses and some other outdoor applications. The Wanamaker store in Philadelphia was illuminated by arc lights in 1878. With the availability of electricity from mechanically driven generators there came an interest in storage batteries. Planté and Fauré invented lead acid storage batteries around 1880. Useful electric motors, again due to Gramme, arrived on the scene more-or-less accidentally in 1873. Incandescent lighting arrived around 1880 primarily as a result of the efforts of Thomas Alva Edison in the United States and Joseph Swan in England. Central power stations began operating in England and the United States in 1882. Four months after starting operation, the Pearl Street Station in New York was lighting more than 5000 lamps for 230 customers. Electricity had arrived and it fueled the demand for larger and more powerful steam engines. Stationary reciprocating engines probably peaked at a few thousand horsepower. As central stations needed more power they added more engines and generators. As noted earlier, these assemblies of large engines were noisy and caused vibration. Fortunately Charles Parson, with a lot of brilliant work, invented the successor to the reciprocating steam engine, the steam turbine. Parson's patent, which was granted in 1884, was the beginning of a long line of turbine patents. These machines were quiet and did not vibrate. They were much more acceptable neighbors. Also, for a given horsepower they were smaller. Because of the smaller size and for other more technical reasons, turbines could be more easily built to produce large horsepower. In the first decade of the twentieth century turbo-generators of 5000 to 15000 horsepower were common. By the 1930's they had grown to the point where turbines producing over 50,000 HP were not uncommon. This takes us to roughly the present day in steam power, there is a parallel story about the development of boilers and nuclear power, but it would take us too far afield for this essay.

The final nineteenth century invention that fits into this story is the internal combustion engine. One might argue that these engines derived from early experiments that lifted a piston by exploding a small charge of gunpowder in the cylinder. It is true that these early experiments were probably known to the internal combustion pioneers, but the problems of cyclically repeating this sort of power stroke were immense. The first commercially practical engine was manufactured by Lenoir beginning in 1860. It was not a very good engine, but it did supply modest amounts of power, using gas as fuel, to locations were steam plants were impractical. By the end of the nineteenth century, Otto and Diesel had made their great contributions and much improved engines, using both gaseous and liquid fuels, were powering early automobiles, supplying power to small shops and driving generators to supply electricity for remote mansions. The evolution of the internal combustion engine is at the same time similar to and different from that of the steam engine. Reciprocating gasoline engines probably peaked in size with aircraft engines that produced 4300 HP with a weight less than one pound per horsepower. In another direction large low speed diesel engines rated at tens of thousands of horsepower have been developed. The reciprocating internal combustion is alive and well! Gas turbines, the internal combustion analog of steam turbines were developed in the 1930's and 40's. Best known to most of us as jets they were originally developed to power aircraft, they now power ships and generate electricity.

Transportation

What I have said up to now focuses on prime movers, sources of power, and how they evolved. These developments have had great impact on the way we live. Perhaps nowhere has the impact been larger than in transportation. Looking first at ships, we note that they went from sail to reciprocating steam engines soon after Watt's "rotative" engine appeared. The next step was the use of steam turbines. Diesel engines are now the plant of choice for merchant ships, while high performance naval combatants use gas turbines or nuclear power (actually steam turbines). If you will indulge me for just a minute, I would like to say just a little about submarine (submersible) propulsion since thinking about that subject led to the title of this essay. Toward the end of the nineteenth century there was great interest in submarines and some experimental types had been developed. None of them, however, provided what was wanted, namely, surface performance similar to a surface vessel and submerged propulsion that did not consume air and which could be replenished while surfaced using only the vessels own resources. John Holland solved the problem. He brought together, my original **confluence**, three nineteenth century inventions: the internal combustion engine for surfaced propulsion, a storage battery to provide the power for submerged propulsion, and a dynamo that functioned as a battery powered motor when submerged and as a generator for recharging the batteries when surfaced. Holland did not invent any of these devices, though he did invent others, his genius lay in bringing together three quite new elements to make a radically new system.

Steam power was unquestionably the driver for the development of railroads. There was no other mechanical source of power and it is reasonable to assert that without steam rail transportation would have had very different, perhaps much smaller or later, history. Steam power, however, gave way to diesel power in the 1930's and there has been significant electrification. Road transportation is a different question. Steam was tried, but it did not work well. The Stanley Steamer is an antique with no recognizable progeny. The internal combustion engine made automobiles practical and gasoline and diesel engines are still the mainstays. The simple fact is that liquid hydrocarbons store more readily useable energy per pound (up to about 20,000 BTU/lb) seems likely to assure that the demise of the internal combustion engine in road transportation will not come soon.

Propulsion was critical in the development of aviation and the internal combustion engine was the first useful aircraft power plant. The Wright brothers calculated that they needed an eight horsepower engine that weighed less than twenty pounds per horsepower. No engines that light were available, but the commercial gasoline engine was only forty years old and development had been oriented toward improving efficiency and reliability. The Wright brothers designed a four-cylinder engine. Their mechanic, Charlie Taylor, built it. After some teething problems (Bishop Wright wrote on 2/13/03 "... The boys broke their little gas motor in the afternoon...") the engine produced sixteen horsepower for a brief period after starting and about twelve horsepower in steady operation. The bare engine weighed just over 150 pounds, well within their requirements. Aircraft reciprocating engines evolved rapidly and at their zenith in the 1950's they weighed in at about one pound per horsepower. Once again an apparent size limitation emerged. Very large aircraft piston engines were notoriously unreliable. Further, propeller efficiency decreased rapidly with aircraft speed. Fortunately experimental work on gas turbines had started in the 1930's. Several jet-powered fighters flew during WW II. The Boeing KC-135, from which the 707 developed, first flew in 1954. The rest is recent history.

Epilog

In the course of writing this essay, I discovered several things that I found very interesting, but which do not fit conveniently into the body of the essay. Many authors, mostly historians and economists, try to find general models for the process of invention. The confluence model is one that sometimes finds favor. I seriously doubt, however, that a meaningful general model can be constructed. Edison noted that he used vastly different approaches for chemical inventions as contrasted to mechanical inventions. It was his "try everything" approach to chemical problems that led to that approach being called somewhat pejoratively "Edisonian".

Chauvinism is endemic in the history of technology and not a purely Russian vice. For example, if one reads American histories one finds that Edison invented the incandescent light. English histories say Swan was the inventor. I believe that both invented the incandescent light and that each benefited from the other's work. In earlier times, say before 1800, communication was much slower and I suspect that independent inventors, in geographically separated places, made the same inventions roughly simultaneously.

The center of inventive activity has moved around in the past few hundred years. In the eighteenth century England dominated, perhaps because of the steam engine. In the early to mid nineteenth century French inventors made some great contributions. Late nineteenth century England and US, twentieth century US

The rate of inventive activity as measured by patents has increased at a staggering rate. In England from 1624 when the first patent was granted to 1769 an average of six patents per year were granted. In the United States 176,191 patents of all types were granted in 2000. In 1984 the number was 71,830. That a growth rate of about 6%/year. Population grew at about 1%/year and when corrected for inflation, the GNP probably grew at less than 4%/year over the same period.