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Reflection

Mechanical engineering design, learning from the past to design a better future?

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Abstract

The economic importance of design, and design engineers to the success of a company has led to the exponential growth in the demand for qualified design engineers. To fill this demand, colleges and universities provide the best training available so that, after graduation these engineers will provide significant input from the first day of work. We live in a time known as industry 4.0 or the 4th Industrial Revolution, where computer power rules and takes on greater tasks, freeing up time for the design engineer to design more and more complex designs.

Sometimes, it is good to stop, and take a breath to review our practices and remind ourselves of things we may have forgotten. It is true that we can design complex mechanisms and systems, in times past many of these would not be possible. But can we learn or be reminded of good practice by taking a journey through some of the design methods from the past. This paper will travel back to the 2nd century BC and look at cutting edge water pump design and the importance of a good literature review. It will highlight a serious gap in knowledge when comparing full-time and part-time students in our modern age. Airship design will be reviewed, the R100, R38 and R101 to remind us of the need to cross check design calculations. Looking at the beauty of Concorde design will remind us of the requirement in any design of good planning and regular meetings. This journey will finish by looking at the design process of the Boeing 777 commercial airliner, one of the first designs to use Computer Aided Design (CAD) and Computer Aided Manufacture (CAM). The use of Design Build Teams (DBT) with cross-disciplinary experts who can reside anywhere in the world will be considered. The reviewed historical examples may at first glance appear happen-stance but are in fact linked, and demonstrate a continuing growth in the ability, knowledge, complexity, and techniques of engineering design.

This step back in time will remind teachers of some basic principles when teaching design to future design engineers. Designs have become more complex in this modern age, but it would be incorrect to say that complex design did not exist in times past. Before the internet, aircraft were built, global communication systems existed, men went to the moon.

Keywords

Design, Teams, Past, Teaching, Industry 4.0, 3D Modelling

Introduction

The importance of design cannot be over-estimated. It is a true and obvious statement that everything we use to-day, everything we have used in the past, and everything we are going to use in the future, a design engineer, or design team created it.

Effective use of design can bring financial benefits to a company. The British government was the first in the world to recognise the importance of design when it set up the Council of Industrial Design, which later became known as the Design Council. The United Kingdom (UK) has the largest design sector in Europe and the second largest in the world. The Design Council (2018), who are an independent charity and government advisor on design make clear the importance of design and designers. Design contributed £71.7 billion to the UK economy during 2018. For every £100 a business spent on design, their turnover increased by £225 (Design Council, 2018). The design economy is adding jobs at more than three times the national average. During 2014, 1.6 million people were employed across the design economy, that is 5% of the workforce in the UK (Design Council, 2018).

For over 50 years, Moor's law has been found true. The number of transistors that can be manufactured on an integrated circuit doubles approximately every 18 months (Swan, 2020). The effect, in computing terms is to produce ever more powerful computers, a new generation of faster computer hardware. These more powerful computers have made possible the development of more sophisticated software. In the early 1980's, to design a complex system required many thousands of two-dimensional drawings on paper, depicting three-dimensional parts. Expensive physical mockups or prototypes were required to check for interferences between parts as these were difficult to impossible to identify using two-dimensional drawings. By the 1990's, as computing power increased it was possible, for the first time, to design a complex system, the Boeing 777 commercial aircraft, not on two-dimensional (2D) paper but using three-dimensional (3D) software (Sabbagh, 1996). The traditional design office was replaced with the design world. Geography no longer limited the designer's world. With the internet, complex designs could be produced using design teams who are not required to be in the same physical space. Physical mockups or prototypes were reduced and often no longer necessary, this could all be accomplished with the aid of the new, more powerful computers (Friend, 2018) (Hombergen & Ploeg, 2018).

Whilst collectively, as a society we can celebrate our advances, it is useful to reflect on a time when such complex designs were possible, without the aid of computers. The design of the commercial airliner Concorde is still considered a marvel of technology but was designed without the aid of any computers. If we go back thousands of years in history, we will see complex designs for that age. Let us look at the design methods used and how these methods changed as complexity of design increased. We will see these 'ancient' methods are as applicable today as they were when first applied.

Reviewing the past to develop and improve methods in the present is not new. Examining case study methodology is a tried and tested process that has helped designers and educators apply lessons from the past to today. Auburn University provides eighteen case studies of real-world examples. Pramod et al (2010) argues these case studies can be used to improve mechanical engineering education. Ceccarelli (2021) discusses looking at machines from the past, and their inventors, to determine the trends for the future. These historical examples can be used to motivate future engineers. According to Kotnour (2015), engineering managers can use the past and present to determine the emerging trends, challenges, knowledge roles, and stakeholders needs of the profession. This paper will continue to apply the basic principle of learning from the past to apply to the present and future.

As the complexity of designs increases, the tools we use to design are also increasing in complexity making the teaching of design more difficult. While these modern tools are important and must be taught, it is important not to forget the tried and tested methods of the past. These are the cornerstones of our modern tools.

Research and Knowledge

Go back to the second century BC to meet Philo of Byzantium. Figure 1 is a reproduction of the earliest drawing of his force pump. The design process revolved around functionality. There is little evidence of refinement or aesthetic considerations, but all the essential principles are presented, and the design is unexpectedly complex (Hurst, 1999). It is unlikely that Philo developed any new materials, as the required technology wasn't available to him. It is more likely that he used whatever came to hand, the things he was already familiar with. The method most likely used to design and build the pump was 'trial and error'. Today we would apply the term 'Iterative Design' where the pump would be built, then modified until the function was acceptable. Each successive modification being less involved than the previous one (Hawkes & Abinett, 1984). Today's designer does not have to rely so much on 'trial and error. Our vastly improved knowledge of mechanical principles and the powerful computers and software available to designers makes 'trial and error' nearly a thing of the past. Nearly, because sometimes, the mechanical principles may need to be developed, and computer software can only work on known problems.

Water flows into the partial vacuum created by the upward motion of the piston, and on the down stroke, with the valves reversed, the water is forced up the pipe into the tank. This was a significant advance, or step change from anything that had gone before. This is considered a dynamic product as there is room for significant product development. This, it can be argued, was an invention.

With most inventions, Philo's force pump was refined and next appears in the form of Hero's force pump (Figure 2.) from the first century AD, some 300 years later. The refinements which are most notable are the replacement of two pipes for conveying water to the tank into one pipe, the single actuation beam pivoting in the center and the introduction of a nozzle. This dynamic product can now be considered static, with very little scope for significant product development. The design process was one of incremental improvement in the functionality and efficiency. Hero could determine, possibly with calculations, that for the same amount of effort, or in the same amount of time, he could pump larger quantities of water when compared with Philo's earlier pump. Hero's force pump is an innovation based on Philo's invention (Hurst, 1999).

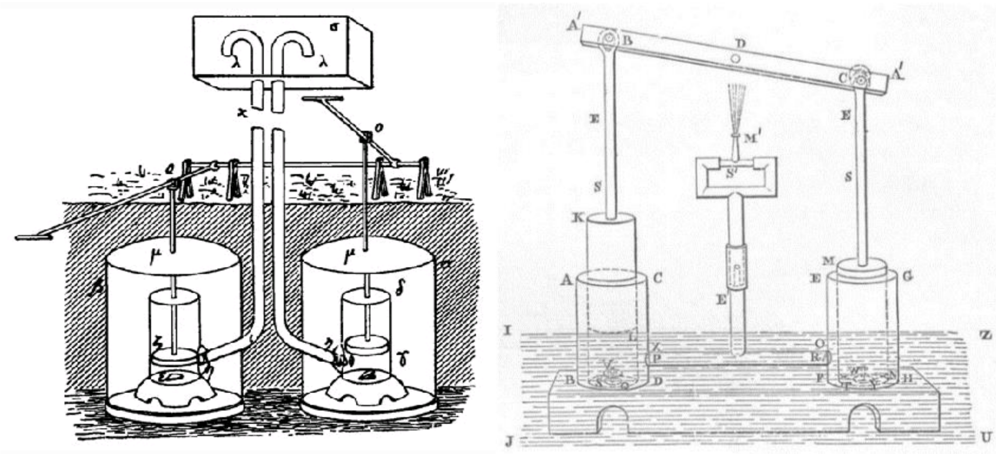

Figure 1. Philo's force pump and Hero's force pump

Moving forward, to the 18th century when Newcomen developed the 'Atmospheric' Steam Engine (White, 2014). Pumps that came before were based on Philo's and Hero's design and were limited by the physical strength of the operator. They could only pump water from a maximum depth of around 12 m (40 ft) as the pumps were drawing water upwards against the force of gravity. The main use of pumps, from Philo's time to the industrial revolution was to pump water out of mines or to provide drinking water. With the power of Newcomen's steam engine, water could be pumped from much greater depths even though its efficiency was only around 8 -10%. This was a dynamic product with room for significant improvement. This improvement came from James Watt's 1769 patented condenser which improved the efficiency of the steam engine to 12 -14% which may not appear to be much but was a major step forward in technology (Selgin & Turner, 2020). The design process of Newcomen and Watt was similar to Philo's and Hero's. The design process was mainly to refine the functionality, to increase the efficiency. The design complexity increase was made possible by new methods of manufacture and materials. With growing knowledge of science, calculations of forces acting on a component could be determined. The Victorians also considered the aesthetics, functionality was important but had to be pleasing the eye.

Early designers probably passed on information by word of mouth. Later they saw the advantages of producing accurate, detailed sketches. Sketches are an important aid in idea generation and a way of piecing together unconnected ideas into design concepts. In our modern era, instead of sketches we use scaled 2D drawings and 3D solid modeling (Dieter & Schmidt, 2009). Most students are adept at using computer graphics and usually have little difficulty in using 2D and 3D Computer Aided Design (CAD) packages, but they struggle to produce useful hand sketches (Stroud & Hildegarde, 2011) and often do not see any need to hand sketch. Sketches should not be considered as less important than 2D drawing and 3D solid modelling produced using computers. The path between sketching of an initial idea and developing it into a finished design is an area that should be given priority in our teaching.

The importance of a thorough literature review is demonstrated here. Hero carried out a literature review and discovered Philo's earlier design. The equivalent of a literature review in Hero's Day involved travelling to the few sources of information available to him. The ancient library at Alexandria with its estimated 400,000 scrolls, or of ancient Rome with their earliest lending libraries (Casson, 2002). These ancient designers clearly demonstrate the importance of a thorough literature review by the effort that was required to achieve it. Most design today is not invention but innovation of an earlier design that is found by carrying out a thorough literature review. We, as teachers must pass on to our students the importance of a thorough literature review. To be thorough requires researching areas that may appear completely unrelated to the planned design project. To illustrate, a well-known brand of washing powder advertise that it cleans using the power of oxygen. This appears to be a rather spurious claim. While researching, would it be obvious to research fishing boats, no, even though fishermen for years have cleaned their dirty clothes by putting them in a net over the rear of the boat (Sailing a Catamaran, 2021). The churning of the propeller releases oxygen which cleans the clothes. Something totally unrelated to washing powder, fishing boats, provided a valuable clue to the researcher. The importance of a thorough literature review and how to achieve it must be taught to our students.

An important part of any literature review is the accumulation of knowledge. Along with researching the latest knowledge, it is important to look at historical knowledge. Hero's design was built on the knowledge of Philo's design, Newcomen's design of his 'Atmospheric Steam Engine' was built on the knowledge of Hero's design. James Watt's improved steam engine was built on the knowledge of Newcomen's design and so on. This process continues into our modern era. Even though we live in an age where knowledge, through the internet is at our fingertips, there are still areas that require the attention of teachers. Basic engineering knowledge, such as use of keyways, selecting bearings, difference between bolts and screws, identifying internal and external circlips etc. is accumulated by engineers everyday they are at work. This knowledge adds up to a vast library of knowledge and is sometimes referred to as 'experience'.

Part-time students at college or university, as an entry requirement, will be in appropriate employment in the mechanical engineering sector. They will be building their library of knowledge or experience every day in work, and at the same time, building their knowledge of complex engineering systems in their studies at college or university.

Full-time students at a college or university will also be building their knowledge of complex engineering systems in their studies. Their library of knowledge will be building, but at a much slower rate than part-time students. This has created a very large divergence in basic engineering knowledge between part-time and full-time students (Sole, et al. 2021).

As teachers, we learn to differentiate in our classes, to allow and accommodate the differences in our students. For design students, this must include the difference in basic engineering knowledge between part-time and full-time students?

Industrial Revolution, Industry 4.0

During the industrial revolution technological changes included new materials; new energy sources; new machines; work was organized into factories; new transportation; and increasing application of science by industry (New World Encyclopedia, 2018). During this period designers and engineers produced some of the world's greatest inventions and designs. The steam engine, telegraph, steam locomotive, submarines, telephones, steamboats, transatlantic cable, the airplane, and the light bulb (Engineering Daily, 2017).

The first industrial revolution, in the eighteenth century started with the introduction of the steam engine which made many manual jobs, mechanized. This was followed by the second industrial revolution in the twentieth century which was driven primarily by electricity. Design during the first and second revolutions was an in-house affair, each company having their own, small design departments. The third revolution, which is ending, was due to the use of electronics and computer technology for automation in manufacturing. Design during the third revolution began with much larger design departments with hundreds of designer's working on more and more complex designs. With the introduction of computers, the design departments became smaller, but the complexity of designs became larger. We are now entering the fourth industrial revolution, also known as Industry 4.0, which uses advanced manufacturing and engineering. The speed of this revolution is unprecedented. Previous revolutions evolved linearly, the fourth is evolving exponentially. The breadth and depth of change will transform entire systems of design, and manufacture (Kenett & Swarz, 2020). This revolution has heralded the design and manufacture of things never even imagined. The mobile telephone with instant internet access, automated factories, large commercial aircraft, communication satellites, self-driving automobiles, and global positioning systems, are just a few of the benefits from the fourth revolution (Pal, 2008).

The challenge for teachers is keeping abreast with the changes. Links with industry help, but unless these companies are cutting edge, world leaders, this source of information will always be slightly behind the latest developments. Trade and journal papers provide information on the latest developments. Research links with industry are a very good way to maintain current knowledge. Current knowledge requires that teachers maintain continually updated course notes with student being made aware that this is the latest data/knowledge they are receiving.

The Age of the Airships

Moving forward to the 20th Century. On 24 August 1921, the airship R38, with a crew of 49 on board was practicing turning trials over the Humber Estuary, UK. This involved turns at full helm and full speed. It suffered structural failure and broke in two, killing 44. During the subsequent investigation it was revealed that responsible officials had made no calculations whatsoever of the aerodynamic forces acting on the airship in flight. No one was sacked over it, or even suffered censure. This same team was entrusted later to the building of the R101, see Figure 3.

In 1924. a small team of 6 - 8 engineers came together to begin design on another airship, the R100. The team was led by Mr. B.N. Wallis, made famous later during World War 2 for designing the Wellington Bomber, the bouncing mine that destroyed the great dams of Germany, and finally some of the largest bombs of the war, Tallboy (6 tons) and Grand Slam (10 tons). The current design practice was for engineers and designers to devise solutions to problems. These solutions were recorded on paper using 2D drawing methods. Due to the increased complexity of the designs 'Calculators', specialist individuals were employed to calculate the stresses acting on the airship frame. This process could take up to 2 - 3 months and began by estimating the forces in the frame, then re-calculating the forces until a satisfactory resultant of zero was obtained. A double check on the results was then made, using a different method. If the calculations were correct, they too would give a resultant of zero. These hand calculations could fill 50 pages of foolscap (Shute, 1956). This is an iterative mathematical procedure in which an approximate solution to a problem is initially guessed and then fed into an iterative formula which reveals a more accurate solution (Hawes & Abinett, 1981). This airship, during its trial flights proved to be successful and safe. The R100 clearly demonstrates the importance of stress calculations followed by re-calculations using different but complimentary methods until satisfactory results are obtained.

Let us now return to the R101.The work on it was finished on the 12th October 1929. Two days later it slipped from the mast at Cardington, UK, on its maiden flight. After several flights it was decided that the lifting capacity of the airship required increasing, and at the same time to initiate as much weight saving as practical. Were these major changes due to a lack of pre-manufacture calculations? The decision was made to insert an extra section in the center of the airship which would increase the length by 53ft from 724ft to 777ft. The gross or total lift was increased to 167.2 tons, with the fixed weight now 117.9 tons, giving 14.4 tons increase in disposable lift to 49.3 tons (Stewart, 1994). After brief trials and a Certificate of Airworthiness that was issued hours before departure, the airship left for a journey to India. In poor weather it made it just south of Beauvais, France where it crashed killing 48 out of a compliment of 54.

The two tragedies of the R38 and R101, both designed by the same team which was known to be lacking in accurate or any calculations, highlights the importance of calculating the forces acting on a component. Today, computer software provides the tools necessary to calculate these forces. A component can be modelled virtually using 3D software. The forces acting on the model can be applied and Finite Element Analysis (FEA), in a fraction of the time, will calculate the forces (Hutton, 2004). But much more is required. Using 3D modelling software is not difficult to learn. Understanding its limitations takes much longer. Students must be aware of the requirement to validate the setting up of the software so that correct results are obtained. SolidWorks, a 3D modelling supplier provides 142 validation examples to help the user understand these limitations (SolidWorks Simulations, 2019).

To back up modern day FEA simulations, calculations based on accepted industry calculations are also necessary. When the R100 was in its design stage, 'Calculators' spent months calculating the effect of forces acting on the airship frame. They backed up their calculations by checking them using different methods. Our students should be taught to calculate then recalculate using different methods. Students often have enough difficulty using one set of calculations and getting them to match the results from FEA. When they do not match, which is right, and which wrong? The more methods students can use to calculate stress the more accurate will be their results. As an example, a basic, but extremely important calculation is that of stress in beams. What methods are students taught? Macaulay's, Castigliano's, Superposition, and Elastic Energy. Any or all these methods can be used to determine the stress in a beam, then recheck it and finally to confirm the results using a validated FEA method.

Concorde

The design and manufacture of Concorde (Figure 4.) was an early example of international cooperation. On the 5th November 1956 the first of 7 meetings took place of the Supersonic Transport Aircraft Committee. Several technical subcommittees each had 12 meetings, Air Registration Board, Aircraft Research Association, National Physical Laboratory, and College of Aeronautics. Finally, Specialist Working Groups met many times. By 29th November 1962 the historic Anglo-French Agreement to build Concorde was signed (Owen, 2001). This agreement provides details of the responsibilities to design and manufacture each country was to assume. Five main areas of equal sharing were stipulated, Structure, Systems, Aerodynamics, Strength and Aero-elasticity calculations, and Weight and Center of Gravity estimates. Later, the aircraft ancillary systems were allocated to each country. A 50/50 split of these areas was the aim. The design process followed a traditional path of design, check, detail design, prototype, test, redesign if required until a desired solution was found. The collaboration allowed each country to designed and manufacture components separately, thus reducing the possibility of both countries design having the same faults, if any. This design process achieved similar results as using 'Calculators' when designing the airships. Two different determinations of forces to reduce or eliminate potential errors.

Nothing like Concorde had ever been attempted before. The technical problems were immense. All parts were designed using 2D systems to represent 3D parts. Only the most basic computer systems existed, so nearly all calculations were carried out manually. The designers could only dream of FEA and virtual mock-ups. Therefore, as Mr. James Hamilton, the Director-General (Concorde) at the Ministry of Aviation said 'This airplane was the most tested airplane of all time. We had rigs for everything,…..we were putting all the systems together under real flight conditions for the first time, you can never be quite sure' (Owen, 2001).

The effect of coordinating the United Kingdom and France's input, designing, and then redesigning, inflation, devaluation, changes in exchange rates, testing, flight testing was shown clearly in the increasing costs. In 1962 the estimated cost was £150-170m. By 1979 the estimated cost had spiraled to £1,129m.

Concorde is an example of teamwork and cooperation between two countries. Regular meetings were held, and clear lines of responsibilities decided upon. The design was world leading which made the development costs extremely high. Software FEA simulation was not an option the Concorde designers had. Even if software FEA simulation was available, it would not have helped with the problems the designers were facing. Software FEA simulation is very good for known problems, problems that the computer programmers could include, but no good for cutting edge design. It is impossible to program any software with data that is yet to be recorded. When teaching design to students, it is vital that they understand fully the software they are using, but more important, to understand what the software is not capable of.

Concorde was one of the first examples of international cooperation and highlights the importance of open communication between design teams, clear allocation of responsibilities and the importance of regular meetings. Colleges and universities should teach students how to work as a team, the importance of regular meetings, how to make clear allocation of work, how to manage a team when things do not go as smoothly as expected.

Boeing 777 – The Computer Age

Design and manufacturing engineers in the early days at Boeing worked around 50 yards apart from each other. When there was a problem in the factory, the engineers went down and looked at it and said, 'Well, you'd better do this.' As the scale of the company grew, designers and manufacturers began to physically drift apart, little enclaves developed. Structures went in one place, air conditioning another. The culture of the company became 'Us and them' (Sabbagh, 1996). This culture was not conducive to efficient design and build.

When Boeing was preparing to design and build a new airliner, the Boeing 777 (Figure 5) they went on a visit to Japan and came across a system called Design-Build Teams (DBT) (Glende, 1997). For the first time in Boeing's history, these DBT would include not just design and manufacturing engineers, but also representatives from the airlines, maintenance organization, marketing, and many others. The design teams worked concurrently on parts, which reduced later modifications, increased efficiency in building and installing those parts. At their peak, Boing had 238 DBT's (Design Philosophies, 2021) (Sharma & Bowonder, 2004). A DBT, working for example on engines would in practice, be working as the early designers and manufacturing engineers in Boeing had but with increased efficiency due to the variety of other representatives in the teams (Birtles, 1998).

For the first time, computers were powerful enough to design 3D parts virtually. Computer-graphics Aided Three-dimensional Interactive Applications (CATIA) format was used. These virtual parts could then be assembled using a second program, Electronics Preassembly in the CATIA (EPIC). Boeing distributed 2,200 computer terminals among its DBT's. All this was connected to the world's largest grouping of IBM mainframe computers (8 off). This system allowed manufacturers in Japan, engine makers in the United States of America and the United Kingdom immediate access to the data.

During the planning phase, justification for the use of a very expensive computer system to design the aircraft was required. The planners looked back at a previously manufactured aircraft, the Boeing 767. They concentrated on certain aspects of its design such as the doors. On this aircraft there was two doors, passenger, and cargo. The doors, during the design phase required 1,341 modifications. The planner's put a dollar value on these modifications and came to a staggering total of $64 million. To put this amount in context, a new Boeing 767, back in the 1970's cost $100 million. When the doors on the new Boeing 777 were designed by two DBT's using the new CATIA and EPIC systems the errors were reduced by 95% which also equates to similar financial savings. Another example was using CATIA and EPIC to check 20 pieces of the flap system. The computer ran 207,601 checks for interferences between parts. A total of 251 interferences were highlighted. These were printed out and at the next DBT meeting it was decided who would be responsible for which interference, saving any possible duplication.

The importance of modern computer systems is emphasized by the Boeing 777 design and manufacture. Today the CATIA and EPIC systems are combined into one system making for even more savings. The importance of design being a team operation was shown by using Design-Build Teams (Sabbagh, 1996). Computers made the complexity of design easier to handle but required teams of specialist to know how to use them effectively.

Conclusion

Looking through this brief history of designing complex components it becomes clear that our ability to design ever increasing complex systems with relative simplicity was built on the shoulders of design engineers who were giants in their fields. Philo's and Hero's Force Pump reminds us of the importance and simplicity of communication using sketches. Computers cannot compete with the simplicity and speed of pencil and sketch pad, yet. To get the most benefit from a literature review, be thorough, and think 'outside the box'. The obvious searches may not always be the ones that provides the most helpful information. The crashes of the

R101 and R38 demonstrate what could happen when designing an airship, with little to no calculations. Compare these with the successful R100, where the stresses in the rigid frame was fully calculated, and once calculated, the importance of double-checking the calculations using a different method. Getting the balance right between software calculations and manual calculations is critical. Concorde's technical design, which still marvels today, must be weighed with the astronomical costs involved in testing and proving not just once but twice for each country involved. The collaboration between two countries in a design and manufacture project identify the importance of regular meetings, and clear allocation of responsibilities. This is even more important today when collaborations between many countries in the design process is normal. The beauty of 3D modelling and advantages in time and money that the Boeing 777 benefited from are important factors but must be balanced with the need to double check calculations as previously mentioned. The strengths that come from working as part of a design team are critical to the success of complex designs today. The Internet takes team working to a planetary scale. Let us provide our students with the necessary team skills to make the most of this development.

We do not have to invent something new or design a world breaking innovation to improve the way we design. By looking in the past and reminding ourselves about things already proven to work we can improve our designs for the future. This paper reviewed just a few processes from the past. These processes are as valid now as they were then. They worked, complex designs for their age were produced. Modern designers just require reminding that these tools are there, proven, tried, and tested.

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