The Key Challenges in Computational Mechanics

by
Klaus-Jürgen Bathe
Massachusetts Institute of Technology
Cambridge
MA, USA

In May of last year, there was a symposium at the University of California Berkeley in honor of Ray W. Clough and Joseph Penzien. I was invited to present at the symposium and my talk was entitled "Key challenges at 40 years after" [1]. Here the forty years refer to the paper by Professor Clough published in 1960, in which he coined the name "finite element method" [2]. While it is difficult to identify who "invented" the finite element method -- and indeed Clough in that same paper says "To apply the Argyris method in the analysis of a plane stress elasticity problem, the first requirement is to approximate the actual continuous system by an assemblage of structural elements ..." -- it is clear that Clough had a seminal impact on the development of the finite element method. Since I was a student of Profs. Ray Clough and Ed Wilson, it was a wonderful honor to address the attendees of the symposium.

Of course, the field of finite element analysis has exploded since the 1960s. The method is now applied in practically all areas of engineering and scientific analyses and is closely related to other numerical techniques, also widely used, such as the finite volume method. For some time, the finite element method and related techniques have been, frequently, simply referred to as "methods in computational fluid and solid mechanics".

With all these achievements in place and today's abundant applications of computational mechanics, it is surely of interest to ask "What are the outstanding research and development tasks ? What are the key challenges still in the field ?" I addressed these questions in my presentation at the UC Berkeley symposium in May 2002 and would like to address them now as well, see also the Prefaces in refs. [3, 4].

While much has been accomplished, there are now -- as much as ever -- most exciting research tasks in computational mechanics. Indeed, we can predict that over the coming years we will attain a new level of mathematical modelling and numerical solution that will help us to reach a much deeper understanding of nature, and that will not only have a continuous and very beneficial impact on traditional engineering endeavours but will also lead to great benefits in other areas such as in the medical and health services (see figures, courtesy of ADINA R & D, www.adina.com). This new level of mathematical modelling and numerical solution does not merely involve the analysis of a single medium but must encompass the solution of multi-physics problems involving fluids, solids, their interactions, chemical and electromagnetic effects; must involve multi-scale phenomena from the molecular to the macroscopic scales; must include uncertainties in the given data and solution results; and, in engineering, must focus on the optimization of designs for the complete life spans of the systems. Based on these thoughts, we can identify

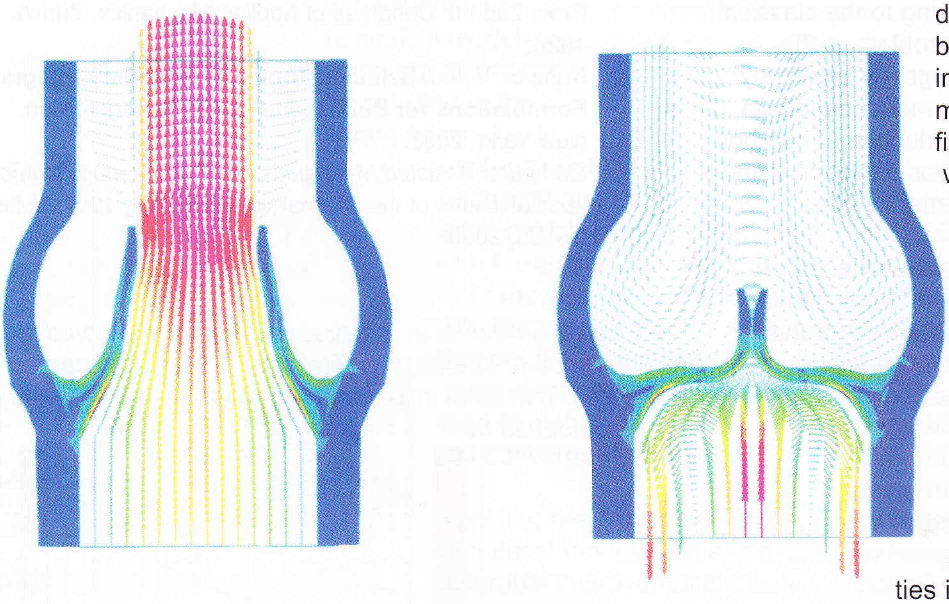


Figure 1:
Aortic valve, open and closed: blood velocities and arterial stresses

the following eight key challenges for research and development in computational mechanics.

Challenge 1.
The automatic solution of mathematical models. Many advances have already been made in the development of numerical procedures, and notably the finite element method, to automatically solve mathematical models for a given accuracy. However, there are many further advances needed in the meshing algorithms, in discretization schemes to have uniformly optimal schemes, in error measures, and so on, including actual practical implementations utilizing advances in hardware. A further step is to automatically create mathematical models, hierarchically, and establish error measures on these models.

Challenge 2.
Effective numerical schemes for fluid flows. Numerous publications exist on the numerical solution of fluid flows, but the numerical methods proposed are far from satisfactory. "Ideal" solution schemes would be much more predictive, reliable and effective. Clearly, major advances are still possible.

Challenge 3.
The development of an effective mesh-free numerical solution method. While much research effort has been expended on the development of meshless methods, only a few proposed techniques are truly meshless and these are not yet sufficiently effective. A reliable, general and efficient mesh-free method for solids and fluids will greatly advance the field of analysis and surely such a method can be developed.

Challenge 4.
The development of numerical procedures for multi-physics problems. One major area is given by fluid flows, including heat transfer, chemical and electro-magnetic effects, fully coupled to structures. Of course, there are in addition many other multi-physics areas involving thermo-mechanical, electro-mechanical, chemical, and other coupling effects. Advances have been made for simulations in these fields but significant further progress can be accomplished.

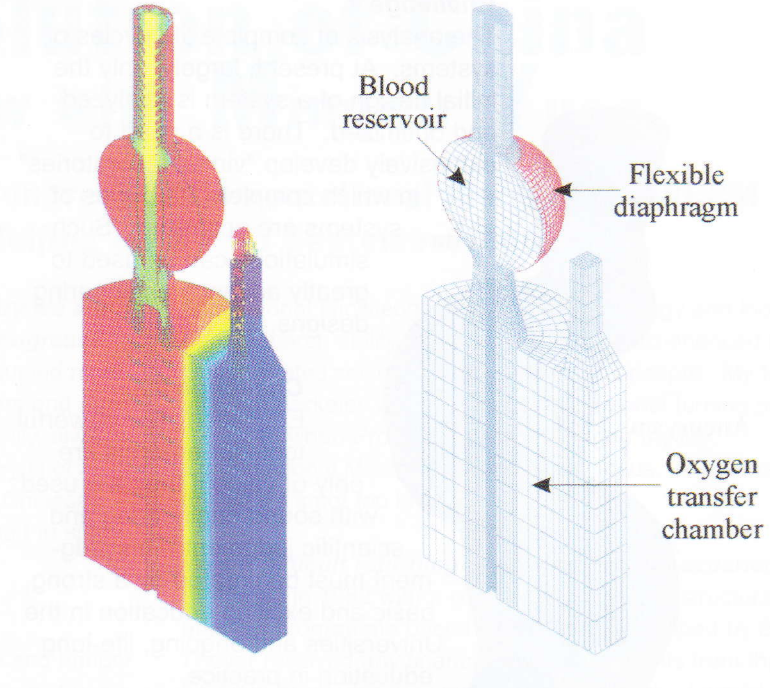


Figure 2:
Artificial lung: pressure, blood velocities and mesh

Challenge 5.
The development of numerical procedures for multi-scale problems. Many devices and phenomena in engineering and the sciences involve multiple scales. The spanning of scales in analyses of engineering designs, notably those using nano-technology, in analyses of bio-medical applications, fluid flows, material modelling, and problems in the earth sciences, to name just a few, provides an exciting challenge.

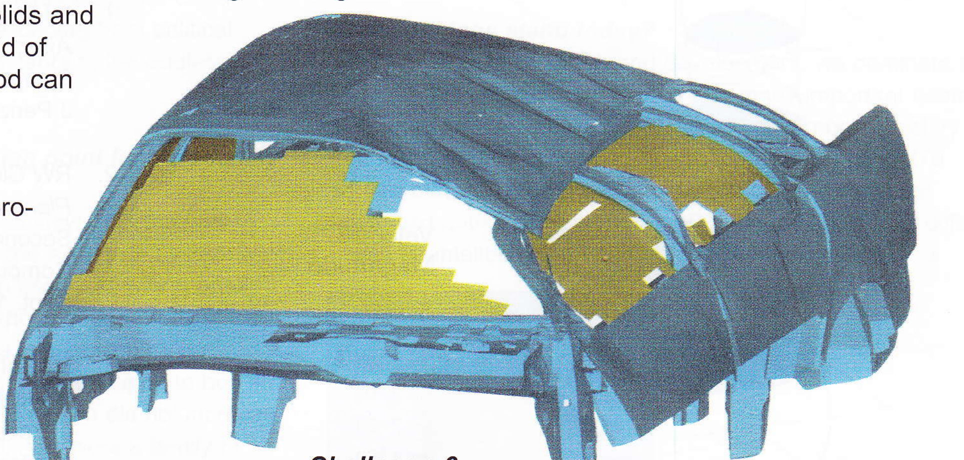
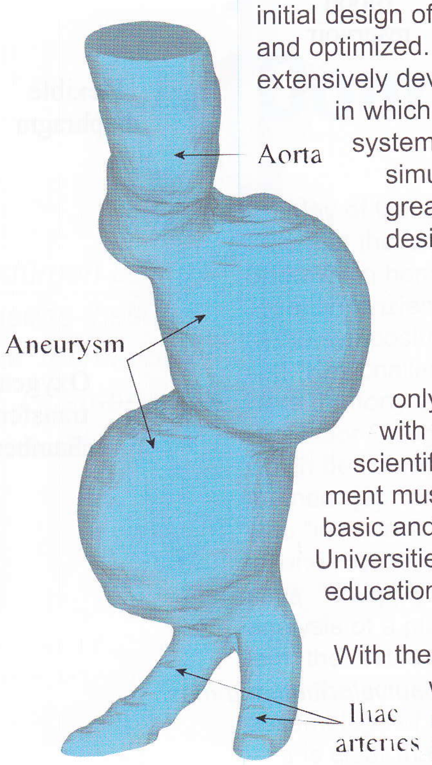


Figure 3:
Crushing of a motor car model

Challenge 6.
The modelling of uncertainties. The purpose of an analysis is to model nature, as represented in a new design or an already existing system. However, invariably there are uncertainties and these ideally would directly be included in many analyses. This will surely be possible.



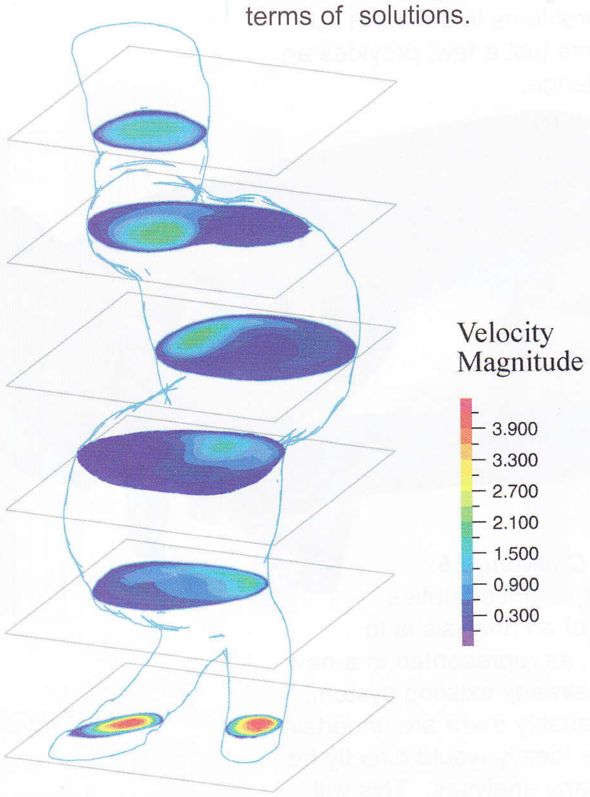
Challenge 7.
The analysis of complete life cycles of systems. At present, largely, only the initial design of a system is analyzed and optimized. There is a need to extensively develop "virtual laboratories" in which complete life cycles of systems are optimized. Such simulations can be used to greatly advance engineering designs.

Challenge 8.
Education. The powerful tools for analysis are only of value if they are used with sound engineering and scientific judgment. This judgment must be created by a strong, basic and exciting education in the Universities and ongoing, life-long education in practice.

With these challenges identified, we of course should ask ourselves "How can we best meet these challenges ?" There are two important tasks.

Figure 4:
(top and bottom)
Abdominal aortic aneurysm: Model and Velocity profiles

Firstly, Industry and Academia should work closely together. History has shown that - frequently - major scientific and engineering developments took place when there was a need for such developments. This need is today frequently driven by what Industry seeks in terms of solutions.



When referring to Industry we do so in the broadest terms. Hence, we include, on the one side, those branches that have used computational methods for some time and, on the other side, those branches that now hardly employ computational methods but could greatly benefit by the use of extensive numerical simulations.

Of course, to meet the above-enumerated challenges it is also much more exciting and valuable - because of the synergy that can result - if Academia and Industry work closely together.

Secondly, we need to make efforts to help the young people who work in the field of computational mechanics. The given challenges will need to be worked on for many years, and it is crucial that bright young people find the area of computational mechanics to be a very vibrant and exciting field to work in.

The future of computational mechanics belongs to the young researchers. It is this generation that will largely meet the challenges and establish the new level of mathematical modelling and numerical solution mentioned above. In these endeavours - namely, the research and development, and the fostering of the young colleagues - there is truly a wonderful future in computational mechanics for all of us, and for many years to come. •

References

1. KJ Bathe, *Key Challenges at 40 Years After,* Proceedings of UC Berkeley Symposium in honor of RW Clough and J Penzien, May 2002.

2. RW Clough, *The Finite Element Method in Plane Stress Analysis*, Proceedings, Second ASCE Conference on Electronic Computation, Pittsburgh, PA, pp. 345-378, Sept. 1960.

3. KJ Bathe, ed., **Computational Fluid and Solid Mechanics,** Elsevier , 2001, (Proceedings of the First M.I.T. Conference on Computational Fluid and Solid Mechanics, June 2001.)

4. KJ Bathe, ed., **Computational Fluid and Solid Mechanics 2003**, Elsevier, 2003, (Proceedings of the Second M.I.T. Conference on Computational Fluid and Solid Mechanics, June 2003.)