

Preface

I was a graduate student in the Department of Computer Science at the University of Waterloo in 1977. One day, Prof. Bill Nicoll, whom I later learned was one of the founders of the University and of the Department of Mechanical Engineering, knocked on my door with his ever smiling face and humble posture. I could not know this would be a turning point in my life.

He told me he had seen my technical note published by the University on the finite element solution of the convective diffusion equation. He then asked if I would like to join his team in the Mechanical Engineering Department and continue my Ph.D. studies there. He also mentioned his plans to visit Prof. D.B. Spalding in London to do a joint study in computational fluid dynamics, and asked if I would be able to accompany him. His offer came as a great surprise, since, as I explained, I had no knowledge of fluid dynamics. I was only a mathematician with some specialization in numerical analysis. He assured me that this would not cause a problem since I would be working on the numerical aspects of the subject. He added that I would also improve myself in due course by taking certain graduate courses in fluids. He gave me one of his latest papers and asked me to examine the partial differential equations in the paper and contact him later.

After I examined the paper I decided to accept the offer, but there was a serious problem. At the time I was newly wed and my wife, Ümit, was expecting our first child in a couple of months; therefore, I had to discuss the issue with her. To my surprise she accepted the idea without hesitation. Soon, I visited Prof. Nicoll in his office and told him of my decision. I expected that it would take some time for my transfer to another faculty, but right away he took me to my new office, which it was already prepared, and insisted that I start work immediately.

Sometimes after my transfer, I learned that the principal of the University initially had rejected my transfer based on his belief that a mathematician would not be successful in engineering. But Prof. Nicoll had insisted that if engineers were successful in mathematics, mathematicians could well succeed in engineering, thus initiating my career in the field of computational fluid dynamics.

Unfortunately, our collaboration with Prof. Nicoll ended after his sudden and unexpected death a couple of months later.

The second turning point in my life was when I met another wonderful man, Prof. George D. Raithby, with whom I worked closely for about four fruitful years until completion of my Ph.D. thesis. He was more than a supervisor to me. He was a friend who insisted being called 'George'; something that, out of respect, I initially had difficulty in doing. Together we completed a comprehensive analysis of the available computational procedures for the solution of incompressible fluid flow problems. We came up with some new ideas on improving the performance of these procedures.

In appreciation of his valuable help, I studied hard to complete my thesis. I well remember that on one occasion, while working late in my office, that the University security officer came and asked me to "ring my poor wife at home as she was worried about my whereabouts."

All the hard work paid off as we came up with a good job which was accepted without any amendment by the examiners. After I finished my Ph.D., Prof. Raithby told me that this was the first time, in the history of the University that a Ph.D. thesis was accepted with no amendments whatsoever. The key to my success was, without doubt, his gentle and kind encouragement and guidance.

I would have dearly liked to have continued working with him to realize the ideas I then had in my mind on the development of new schemes on the subject; of which, arising from my unique situation as a numerical analyst, the feeling that a procedure which would directly make use of the most naive form of the discretized governing equations may work better. After all, as Albert Einstein's said "God does not play dice." In fact, every physical process in nature works in a superbly designed mathematical mechanism. Therefore, why do we try to make physically unrealistic assumptions about nature, instead of making use of this nice formulation in its primitive form?

Unfortunately, my new adventure in founding the Eastern Mediterranean University (EMU) in my native country, Cyprus, prevented me from continuing to work on this subject, at least for some time. This was mainly due to the lack of computing machines at EMU such as those at the University of Waterloo.

It was only after the introduction of personal computers at EMU in the early 90s that I was able to return to the subject and start to implement some of these ideas by directly attacking the primitive form of the equations. In the meantime, a few papers were published by Prof. Raithby and his colleagues. They were reporting that keeping more effects of the coupling between the pressure and velocity fields significantly decreased the need for high under-relaxation by enhancing the range of convergent relaxation parameters. I shared their belief. Surprisingly, however, the overall convergence of the proposed procedures was not much of an improvement on the segregated ones.

Unfortunately, after these findings were published, researchers reverted to the old procedures and thus research in this regard was terminated. There was an unspoken acceptance that any attempts to solve the equations in their primitive form were to no prevail.

I had the feeling that something was going wrong, not with the basic idea, but with the solution procedures themselves. Otherwise, considering the indications, the performances would have been much better. I encouraged one of my Master students, Türkan Güngörmüş, to work with me to understand this dilemma, but our efforts were not fruitful and resulted in similar conclusions.

I did not give up. After further work on the subject, I realized that the main culprit was sneaking in the reordering of the equations. In fact, the reordering applied was worsening the diagonal dominance of the coefficient matrix, thus slowing the convergence of the iterative process.

Based on this observation, I decided to accept the primitive form as it is, and try some new ideas on the solution algorithm. A natural equation for pressure lay there in the equations, but the main diagonal sub-matrix for pressure was null. Although it was possible to collect nonzeros to the sub-matrix, it would result in a Poisson form, which I would not prefer. Then, I noticed that an incomplete decomposition of the primitive matrix helps, not perhaps in creating nonzero terms in the null part of the original coefficient matrix, but in the main diagonal coefficients of the sub-matrices of the incomplete decomposition. That would be enough for me.

It was not really easy to see what the underlying equations were, so I had to work on long sheets of joined-up squared papers. I multiplied the decomposition matrices and equated them to the primitive matrix. There it was. I had a few nice-looking equations that would give me what I was looking for.

It was a quick implementation of the algorithm that gave me the actual surprise. The algorithm had worked well; it was converging twice as fast when compared to the best segregated procedure. Furthermore, the range of convergent relaxation parameters was broadly widened. This was like replacing my old car by one with a turboprop.

The most satisfying side of this achievement was that at last we got rid of the Poisson-type equations.

It was only then that I went back and examined what the mechanism of the derived equations was doing to invoke such a remarkably well-working procedure.

I realized that the mechanism engineered by the equations not only brings together the effects of the coefficients from the velocity field, but also all of the effects of the mass conservation constraint and all of the effects of the coefficients of the pressure terms in the momentum equations.

After the publication of my first paper on the subject, I concentrated on the improvement of the algorithms by trying various kinds of placements of the vectors in the incomplete decompositions. This turned out to be fruitful, from which came the procedures named FICS (Fully Implicit Coupled Procedure) in this book. The procedures converged about 20 times faster than the segregated procedures and convergence was achieved even without any relaxation. Although the derivation of the relevant formulas was not straightforward, the derived formulas were so simple that they allowed an easy implementation of the solution process.

Following this achievement, I decided to share my findings with other researchers. It was not possible to fully express myself in a journal paper form, so I decided to write a book about the subject.

While working on the manuscript of the book, I was still skeptical on the actual physical reason for the overwhelming performance of the procedures. Numerically, there was no problem and everything was working much finer than I would ever dream of. However, there should have been a meaningful physical explanation to this as well. Finally, I realized that the procedures were actually centralizing on the most fundamental flow property of incompressible fluids.

This important property, which was unfortunately overlooked in the past decades by researchers, including myself as well, was in fact, one of the fundamental rules of fluid flow.

A fluid particle may only move from one point to another if there exists a pressure difference between the two points. The movement is initiated and dictated by the pressure differences characterized by the pressure derivative terms in the momentum equations. While this movement is underway, the particle's velocity components must obey the mass conservation constraint. Thus, the effects of the pressure derivative terms in the momentum equations and those of the velocity derivative terms in the mass conservation equation are equivalently important. These effects are related directly to the fluid flow, but not to the physical fluid properties governed by the diffusion and convection terms.

Therefore, in order that a solution procedure be more efficient, instead of concentrating on the convection and diffusion terms, as was done with the segregated procedures, it should have concentrated on the correct imposition of the pressure changes as well as the mass conservation constraint in all stages of the solution process. The physical properties could perhaps be taken care of in due course.

To put it more precisely, the effect of the pressure terms, in parallel to the mass conservation principle, should have been regarded as a constraint, perhaps to be better named as "pressure conservation constraint."

The mechanism engineered by the new family of procedures was in fact, incorporating this new viewpoint into the solution process. Consequently, this constituted an efficient remedy for all of the problems that were encountered in the classical segregated procedures. The endeavor of creating an explicit pressure Poisson equation in these procedures was actually disrupting the vitally important coupling between the velocity and pressure fields.

Presentations in journal article form do not contain any details, but only vast amounts of references to previously published articles. Consequently, a novice engineering graduate or a field engineer needs to spend months researching these multifarious papers in order to grasp the details involved in the solution processes. These efforts usually end up in a complete frustration and failure to actually implement the procedures.

Books written in this area are usually engineering based and do not address mathematically oriented researchers. They do not either contain adequate information regarding the computer implementation of the procedures. As a mathematician, I accept that some knowledge in the engineering side helps, but when it comes to the development of better numerical algorithms, engineering matters become less important.

Postgraduate books written by mathematicians, on the other hand, are often too general. They are too much theoretically oriented and consequently suffer from heavy mathematical notation. As a result, engineers without deep mathematical theory cannot make direct use of the material.

I always recall and believed in Prof. Nicoll's thoughts; mathematicians with a good knowledge of numerical analysis have much to contribute to the field but always in collaboration with engineers. From such a collaboration more fruitful results will emerge.

On the other hand, it is unfortunate that an experienced researcher or an application specialist is usually reluctant to try and adapt to a new solution procedure. There is already a working procedure at hand, so why spend valuable time on trying to switch to a completely new algorithm even if the new algorithm may work better?

Being aware of all of these facts, I decided to write the book in order to aid both researchers and engineers in this regard. Strictly speaking, I would have never attempted to write such a book if the performances of the new procedures were not so wonderful. My decision came only after realizing that the new procedures would be foundational to a new generation of efficient and robust solvers for fluid flow problems.

With this in mind, I tried to design the book in such a way that a novice researcher can easily find only the specific material required in order to be able to write his own code, without much mathematical frustration. For the experienced researcher, I included various hints and tips so that the algorithms can be adapted to their existing codes quickly, without any problem or fear of failure. For this purpose, I have included FORTRAN codes for some of the procedures which may be called up directly. The only thing that an experienced researcher might need to do is to incorporate the boundary conditions describing the physical problem in a proper fashion and then call the routine, as described in the book.

I tried to do my best in smoothly introducing the new procedures and in designing the book so that it can further be used as a graduate textbook for engineers as well as mathematicians. With its present form, I hope that it can help in bridging the gap between the two disciplines and also act as a reference book for the experienced researchers.

I wish to acknowledge the late Prof. Bill Nicoll who introduced me to this fantastic field of science and to Prof. George D. Raithby for his enthusiastic encouragement that helped me progress in the field.

I would also like to express my special thanks to my wife Ümit, my son Erden, my daughter Eliz, my daughter in love Esin and my grand daughter Derin for their patience and loving encouragement during the course of writing the book. They deserved much more attention than I could devote to them during this time, but now I hope I will be able to redeem myself.

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An Engineer's Resource Book

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