# EARLY DAYS OF TWO-DIMENSIONAL FOURIER TRANSFORM NMR

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When I decided to leave Zürich in the autumn of 1974, after passing the last exams of my diploma in chemistry at ETH, I did not have a clue what I was heading for. I had visited Oxford to meet Ray Freeman in July of that year. He had taken me to have sandwiches in a wonderful pub on the Thames – I believe it was called The Trout Inn – but I was intimidated by Ray's presence, unfamiliar with colloquial English, more comfortable with "Sir" rather than with "Ray". I was delighted by the Oxford setting, feeling intuitively that it would do me a lot of good, after four years in a rather frigid atmosphere in Zurich, where I had completed a Master's thesis under the supervision of Richard Ernst. Its subject (Overhauser effects with multiple selective irradiations) seemed to be a bit exotic, and I did not feel that Richard cared much about the subject.

When I arrived at the Physical Chemistry Laboratory (PCL) on South Parks Road, I met David Turner, who was at that time a "Part II" student (similar to a Master's). David had unpacked and fired up a brand-new Varian CFT 20 spectrometer, which was designed for carbon-13 NMR at 20 MHz, with a proton channel at 80 MHz designed for noise decoupling. This was our only machine for the next three years. In the following months, Gareth Morris was to join our group, initially as Part II student, before starting on his DPhil, soon to be followed by Reinhard Niedermeyer. Malcolm Levitt joined the team when I had just submitted my thesis.

Ray Freeman did not spend much time in the lab, for he was deeply involved in teaching tutorials, i.e., meetings with a handful of students, mysterious rituals that seemed surreal by ETH standards. But Ray often came to coffee or tea breaks in the Common room of the PCL, around 11 am or 4 pm, less frequently around 1 pm for lunch, consisting of a bowl of soup and a roll with cheese, all served by a charming tea lady named Gladys. It is in the Common room that most interesting things happened. When we were particularly excited, we would discuss non-stop from 11 am to 5 pm, over coffee, soup and tea.

Indeed, these were exciting times. We learned to master the timing of crazy pulse sequences on our CFT 20, which had never been intended for anything sophisticated. We programmed in octal code, since there was nothing like a compiler. The entire memory of the Varian computer was limited to a mere 16 k words. The external Diablo disk had a capacity of 1 Mbyte, and we had to instruct the computer to save and retrieve data by indicating the physical addresses of the tracks on the disk.

Ray had a remarkable intuition for the behaviour of classical magnetization vectors and their trajectories. Some of his talents would be revealed after my stay in his lab, when composite pulses became fashionable. In my days, our greatest achievement was a simple sequence of equidistant pulses that was to become known as 'Delays alternating with nutation for tailored excitation' (DANTE).[1] The pinnacle of my skills was reached when I managed to program in real time two such sequences running with different intervals simultaneously, although this was never used for anything.

Then came the totally unexpected advent of two-dimensional Fourier transformations. Initially suggested by Jean Jeener, the idea came to us through a TAMU newsletter by Richard Ernst.

(Only many years later did I become aware of Jean Jeener's lecture in Baško Polje.) This was to become a true passion for me. I remember a social gathering where I pulled an early 2D spectrum from my pocket to show it to the bewildered attendants, much to their dismay, for they must have thought that I suffered from some weird delusions. We discovered all sorts of things, such as artefacts that Ray affectionately dubbed "ghosts" and "phantoms". The invention of phase-cycles allowed us to get rid of both ghosts and phantoms.[6] We liked to speak of Exorcycle, after a silly movie called 'the Exorcist'. We also invented what later came to be known as 'time proportional phase increments'.[8]

We spent most of our time exploring 'J spectra', where the evolution period contained a refocusing pulse to remove line-broadening effects due to inhomogeneous fields.[2,3] (My inability to shim the magnet provided a powerful motivation!) To our surprise, we noted that spin-echo spectra could feature negative lines.[7] We managed to explain these, and Gareth did a great job at adapting spectral simulations ('Son of Laocoon'.[11]) We found some curious effects of interference with sample spinning[15] that would later become relevant in solids.

We re-invented heteronuclear correlations, by invoking the role of populations where information could be stored temporarily.[9,10] The original work by Maudsley and Ernst did not mention this concept. Indeed, the question in which order pulses should be applied to protons and carbon-13 nuclei is immaterial, because the operators that represent the corresponding rotations commute. But this sort of reasoning was far beyond our understanding.[16] In retrospect, the most remarkable feature of my days in Oxford is that we invented so many novel things without a sound theoretical basis! Little by little, we learned to work with density matrices,[11] and came to realize that unitary rotations could be expressed by manually calculating products of 4×4 matrices…

Ray maintained friendly relationships with his former employer, Varian Associates in Palo Alto, especially though Howard Hill, who came to see us in Oxford once in a while. This contributed to fruitful collaborations.[15] In the course of the years, I have tried to foster collaborations between academia and industry in various areas, such as optical 2D spectroscopy with laser pulses, 2D microwave spectroscopy, 2D-ESR, and 2D ion cyclotron resonance mass spectroscopy (FT-ICR-MS). Not surprisingly, many of these attempts have been less successful than 2D NMR, not only because their advantages were less spectacular, but because the instrument manufacturers were attracted to more profitable projects.

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