PROCEEDINGS OF SCIENCE

You can't design what you can't conceive – a theorem!

R H Frater
ResMed Ltd
1 Elizabeth Macarthur Drive, Bella Vista, NSW 2153, Australia
E-mail: bob.frater@resmed.com.au

In looking at the Antikythera mechanism and its purpose, one wonders on how the multidisciplinary knowledge and skills in mathematics, astronomy, geometry, mechanics and craftsmanship could have come together under a "system thinker" leader to produce something so far ahead of its time.

One is compelled to ponder on the environment that allowed this.

In this paper, I consider the work of some of the radio astronomy pioneers who were my mentors and look at the environment in which they produced breakthrough ideas and the benefits that flowed through for radio astronomy and to me as an individual.

My overwhelming conclusion is that similar conditions must have existed at the time the Antikythera mechanism was devised and built.

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1. Introduction

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2. CSIR(O) Radiophysics Laboratory

The Radiophysics Laboratory was formed in 1939 under the leadership of D.F.Martyn to work on the development of Radar. The Radiophysics Laboratory was part of CSIR (now CSIRO) Australia led by chief executive, later chairman, Sir David Rivett. The Division developed a Shore Defence radar and then Air Warning radars.

Martyn was replaced as Chief of Division by F.W.G.(Fred)White in 1942. White recruited E.G.(Taffy) Bowen in 1944 on a visit to Washington.

From early 1945, after White moved to the CSIR Executive, and continuing after World War 2, the Radiophysics Laboratory was led by Taffy Bowen. Taffy established a Radio Astronomy group under Joe Pawsey, a man who was an absolute believer in the "Rivett philosophy", described by Paul Wild as: *"The famous Rivett philosophy was to determine the field of study that you want to do, find the best man in the world you can get to lead the group, and then give him his head."*

Radiophysics became a major Radio Astronomy centre housing some great pioneers in the field.

The Radio Astronomy Group came from a variety of backgrounds. They had degrees in science and/or engineering and had had a variety of wartime and early post-war roles. These included radar development in the UK and Australia, operational navy radar, communication antenna design in Australian company AWA, and work on air navigation and early computing development. They had all experienced the wartime pressures to succeed and worked in collaborative environments.

Their breadth of experience and training provided great opportunities for cross fertilisation.

Joe Pawsey was a key player in Radiophysics, a great leader, described by Chris Christiansen as a man in the mould of David Rivett, the first Chief Executive then Chairman of CSIR mentioned earlier.

The group in Radiophysics had developed a can-do, must-do attitude and culture during their WW2 work that carried over into the radioastronomy era and beyond as the people moved on to other roles. Joe was very much part of this – a proponent and practitioner of the need for System Thinking and Physical understanding.

Joe understood the need for people who can think at both the system level and the component level so that they are able to work from the system level to detailed design and component assessment. He knew that without that you can't subdivide a big system into parts that will integrate properly later[1]. And so to my theorem-

You can't design what you can't conceive

3. Ingredients for Success

This brings us to a consideration of the ingredients for Success in bringing new ideas to fruition:

- There must be an existing or emerging need
- Someone with "fire in their belly" and a clear view of the goal is needed - A champion
- Mentors, People providing example and guidance, are desirable
- A supportive environment is desirable
- The necessary material and intellectual resources should be available
- You need people with system thinking ability and physical understanding
- A sponsor is desirable, someone in a position to help who appreciates and supports the goal

There are, of course, many examples of people who have succeeded "against the odds".

4. My Early Career and Mentors

I had worked as a trainee with AWA during my engineering course and worked with OTC Australia and Ducon Industries after graduation. In 1961, Ron Aitchison invited me back to the university to work on the electronics for the Sydney University's Molonglo Mills Cross near Canberra, Australia. Both Chris Christiansen and Bernie Mills had left Radiophysics in 1960 to come to Sydney University and collaboration was established between Electrical Engineering and the Physics Department to work on the Mills Cross.

As my career developed, I was very fortunate to have a number of great mentors across the Electronics, Electroacoustics and Radioastronomy areas.

In the electronics area, these included Ron Aitchison, an Associate Professor in Electrical Engineering at the University of Sydney, Australia, who was my PhD supervisor, and Cyril Murray from the same department. Ron and Cyril were involved with Bernie Mills' Molonglo Cross. Both were system thinkers. Both had taught me as an undergraduate and were hugely supportive of some of my way-out ideas.

Neville Thiele was a gifted Australian engineer who worked with electronics company EMI and then the Australian Broadcasting Commission and had close connections with the Electrical Engineering School.

Some of my work came to the attention of Kevin Sheridan, Paul Wild's "right had man" and I soon found myself interacting with the Radiophysics group - oblivious of the tensions between the "Parkes Telescope" group, Chris and Bernie. It was then that I first met Paul Wild.

Visits to the Physics Department brought me into contact with Hanbury Brown and then with Ron Bracewell during one of his visits.

My mentors and their mentors had the capacity to hold and manipulate a complex image or concept in their head. They were "System thinkers". They had the authority to implement

[1] (Richard Feynman had strong views in this space)

decisions flowing from their deliberations on these concepts and were not blocked by people who were unable to grasp the broader issues. They contributed to my and others' development by their advice, encouragement and their maintenance and defence of those aspects of the work environment necessary for the development of new leaders. They were able to conceive their new analysis, approach, design.

4.1 Aitchison, Murray and Thiele

Ron Aitchison was a superb teacher/mentor across the whole electronics, telecoms space. He had had early involvement with transistors, and he provided strong guidance of the Electrical Engineering involvement in the Mills Cross project.

Cyril Murray was the electronic designer extraordinaire who achieved prominence as he brought audio amplifier design (Murray Amplifier) with both vacuum tubes and transistors to a new performance standard. Cyril introduced a different approach to thinking and analysis in analog electronics and encouraged novel and "disruptive" approaches from others.

Neville Thiele applied filter design techniques in TV IF design to achieve phase linearity and "ring-free" pictures in EMI TV sets. He then applied filter design techniques to loudspeaker enclosure design[1]. Neville achieved global recognition in this area.

I approached Neville after his 1961 landmark paper on the design of loudspeaker enclosures was published. He was delighted to spend time with a young graduate engineer and we became life-long friends. He was very supportive of my work in the electroacoustic field.

Neville's work was focussed on "getting it right" at a quite fundamental level. The results brought people "back to basics" and were very "disruptive". His approach to loudspeaker design is recognised in the Thiele-Small Parameters for loudspeakers.

Cyril Murray and Neville Thiele were disruptive contributors in Electronics and Electroacoustics.

For an electronics/HiFi nut like me, guidance and friendship from these boundary-pushing people was a great gift.

4.2 Christiansen, Mills, Wild and Bracewell

The early radioastronomers succeeded because they invented the new approaches that were needed.

Chris Christiansen had been involved in the design of Rhombic Antennas at AWA for the Beam Wireless system[2] - the forerunner of OTC, the Overseas Telecommunications Commission. When he used the arrays on the side of the dam at Pott's Hill to scan the sun, he saw the possibility of forming 2D Images from these, the approach being a forerunner of Earth Rotational Synthesis.

In his early interferometer work, Bernie Mills saw the possibility of positioning interferometer nulls on interfering sources to reduce confusion. He then arrived at the concept of the cross radiotelescope.

Paul Wild deduced the mechanism of solar bursts. Saw the possibility of H line in the solar bursts.

Ron Bracewell[8,9] applied the transform concepts from his PhD work with Ratcliffe. He correctly saw the Pott's Hill scans from Christiansen's interferometers as convolutions.

These four all cited Joe Pawsey, a true system thinker, as a mentor.

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4.3 Hanbury Brown

Hanbury Brown and Richard Twiss conceived and developed the technique of "post-detector correlation". Hanbury went on to build the Stellar Interferometer in Narrabri, Australia.

5. Joe Pawsey's leadership and mentoring

Joe Pawsey had a remarkable ability to recognise the strengths of those in his team and steer them to programs where they could shine.

Chris came in from antenna development in Australian company AWA to a senior role in Radiophysics and Joe rapidly made him lead researcher for the solar research program. Chris' own practical approach made for easy communication with Joe Pawsey and he strove to emulate Joe in his own career.

Bernie Mills went directly to Radiophysics after graduation in engineering at Sydney University. Bernie's comments capture other key elements of the Pawsey approach:

> *"Joe Pawsey was in charge of the general development . . . . .work and I learnt a great deal from him. He was always available . . . . I attended a short course of lectures which he gave on transmission lines and antennas which was a real eye-opener. The highly mathematical approach to which I had been exposed during my last year in Engineering was replaced with a physical understanding . . . . . . which stood me in good stead thereafter."*

Joe gave Bernie the choice between working on the H-line or developing interferometry. Bernie chose interferometry.

After a year in Radiophysics Paul Wild was delighted to be able to join Pawsey's group and was given the task of developing a solar spectrograph:

> *"Joe just provided ideal conditions, an ideal environment to allow everyone to use their own initiative".*

Ron Bracewell worked with Pawsey before going to Cambridge in 1946 to study with Ratcliffe, Pawsey's PhD supervisor, who stimulated his interest in the Fourier Transform. He returned and worked with Pawsey's group.

When Pawsey asked him to be co-author of the book **Radio Astronomy (1955)[3],** Bracewell surmised that this was partly a device to get him more interested in the subject. Pawsey also asked him to produce a pictorial dictionary of Fourier Transforms, which later led to Ron's most important book, "The Fourier Transform and its Applications"[9].

Each of these people came up with ideas and solutions that required them to step outside simple problem solving approaches and bring together concepts, analysis and technology. They each had the ability to conceive appropriate solution paths.

All were stimulated by those around them and by their work environment.

To have a real appreciation of achievement, we must think of these examples against the backdrop of the technology of the time – key ideas came up way before the modern "solid state devices" era and years before the zero point of Moore's Law.

The examples I've chosen were **big** steps at the time.

5.1 Chris Christiansen

Christiansen conceived ways to formalise and extend the design of Rhombic Antennas[2] for telecommunications in the AWA Beam Wireless section – the fore-runner of OTC which

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ultimately merged with Australian telecomms provider Telstra). The beams had to be set in azimuth and altitude to achieve the appropriate reflections from the ionosphere for "round the world" communications. As a young engineer in OTC, I used his graphs and tables to design antennas for the field stations at Doonside and Bringelly, near Sydney.

After observations of two solar eclipses during sunspot activity in 1948 as a means of achieving high resolution, Chris saw the need for regular observations of the sun and, understanding of properties of grating array, Chris built arrays on the banks of the dam at Pott's Hill where he was able to get 1D scans of the sun as it drifted through successive lobes[4].

Chris recognised that the angle of the scan changes with the rotation of the Earth and conceived an approach to obtaining 2D images of the Sun using earth rotation synthesis[5].

5.2 Bernie Mills[6]

Bernie Mills concluded that by positioning antenna nulls on interfering sources in his interferometer work he could reduce confusion. He offset one of the antennas in declination so as to position its null.

In a discussion of imaging with Chris Christiansen, Bernie saw that if Chris' arrays were in the form of a cross, one could form a beam. He conceived of a Cross having a pencil beam corresponding to the overlap of the fan beams. This led to the first Mill's Cross and the first catalogue of southern radio sources.

Bernie was faced with the question of how to obtain the information in the fan beam overlap area. He saw that if you multiply the signals from the two arms by phase switching one, adding them and passing them to a square law detector, he would obtain:

$$((E\text{-}W) + (N\text{-}S))^2 = (E\text{-}W)^2 + (N\text{-}S)^2 + 2(E\text{-}W)\times(N\text{-}S)$$

The last component appears as a square wave that can be demodulated to obtain the product. The squared components add noise in this case. And then, by subtracting the difference of the squares from the sum of the squares of the signals, the squared components cancel – reducing noise

$$((E\text{-}W) + (N\text{-}S))^2 - ((E\text{-}W) - (N\text{-}S))^2 = 4(E\text{-}W)\times(N\text{-}S)$$

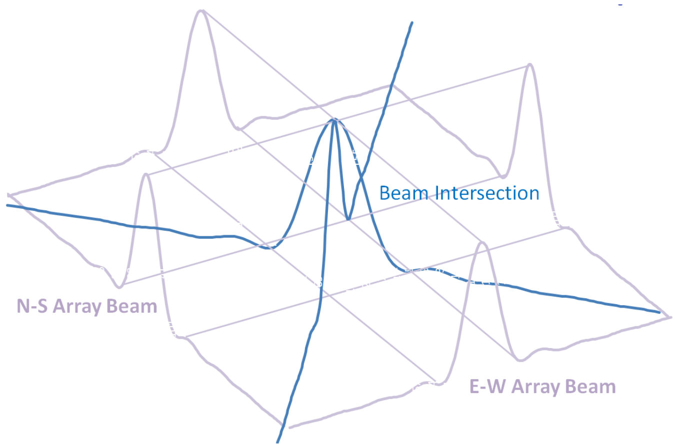

Fig 1. The beam intersections for the Mills Cross

5.3 Paul Wild[7]

Paul conceived the use of dynamic spectra as a path to understanding the physics of solar bursts. In the course of his observations he observed and named a number of different dynamic spectra, leading to the now accepted classification system.

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Paul suspected that there were spectral lines in the solar burst they were observing, became interested in the radio spectrum of hydrogen and wrote an internal CSIRO report.

After the Ewen and Purcell 21 cm hydrogen line detection in 1951, Paul generalized his report to include the hyperfine structure of hydrogen, and published the first detailed theoretical paper on the hydrogen lines – a classic in the field.

Paul saw the need for high speed 2D imaging of the sun, leading to the proposal for the heliograph. For the design, he settled on a circular array– a radio-frequency simulation of an optical device, as the best way to achieve an acceptable side-lobe structure.

As a footnote, when the heliograph was being built at Narrabri and the Chris-Cross at Fleurs was being renovated as the Fleurs Synthesis Telescope, Kevin Sheridan remarked to me "The good thing about a circle is you can't extend it".

5.4 Bracewell

Ron Bracewell conceived the mechanism of the Pott's Hill scans as being convolutions. He explained the scanning of a source by an antenna as a convolution of the brightness function and the point-source response of the antenna. By using the convolution theorem it was clear that in the process the Fourier components of the source profile are filtered by the Fourier spectrum of the antenna response. He developed the concept of "aerial smoothing" and the "principal solution" (with Jim Roberts)[8].

Ron developed the transform relationships involved in reconstructing two-dimensional images from one-dimensional scans.

It was Pawsey's promptings for a pictorial dictionary of transforms led to Ron's classic book on the Fourier Transform[9].

6. Hanbury Brown[10]

Hanbury conceived the fact that the noise fluctuations in separated radio receivers would be correlated leading to the principle of the intensity interferometer using "post-detector" correlation. With Richard Twiss, he successfully demonstrated an optical version in a climate of absolute disbelief in the optics community, by using search-light mirrors to observe Sirius.

Hanbury went on to construct the Stellar Interferometer in Narrabri and measured 32 stellar diameters over an eight year period (Hanbury Brown, Davis, Allen 1973).

The technique is now commonly used in quantum optics as the HBT effect.

7. A couple of my own examples

Both examples represent "physical understanding" influenced by my mentors and bring together ideas from different areas.

7.1 Representing 3D data in 2D[11]

I conceived a convolution approach for reducing 3D data to 2D that came from applying modulation theory to "spatial" frequencies.

I saw that off E-W spacings give a frequency change across field as the projected baseline changes. I saw this as Frequency Modulation where the off-axis spacing can be represented by a central on-axis spacing with the equivalent of FM sidebands. A convolution function can be derived to achieve this. This would be incorporated in the "gridding" of individual spacings.

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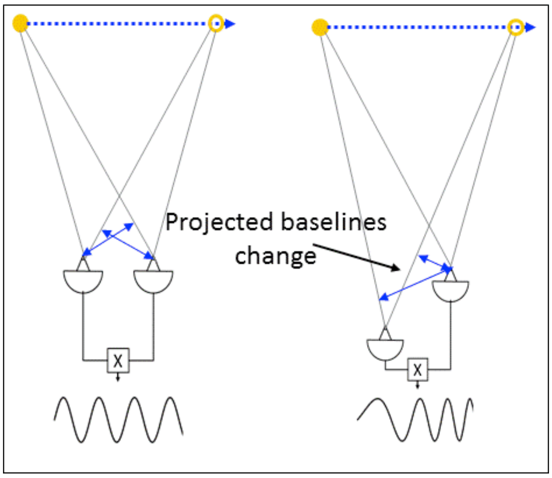

Figure 2. Frequency modulation of "spatial frequency"

7.2 The ColFet[12]

The ColFet is an active circuit that looks like a cold resistor. The concept came from a confronting system realisation and the application of bipolar transistor analysis approaches to a FET circuit. Both are the product of having had the opportunity to work and gain experience across a large system.

It suddenly dawned on me that if we have a low noise amplifier with a matched resistive input, the input resistance must look "cold". In an approach developed with FET amplifiers, an inductor was used in the source lead of the FET. The input capacitance (capacitive reactance) of the FET effectively gave it a complex current gain so that the impedance seen at the input was this current gain times the inductive reactance and was thus resistive.

This resistance was produced entirely by reactive components so that no noise was contributed other than from losses and intrinsic resistances in the FET itself. These intrinsic resistors were the only source of noise and so the input impedance looked like a cold resistor.

8. . . and the ingredients for success?

It is very clear that all the ingredients: a need; a champion; mentors; a supportive environment; resources; physical understanding; a sponsor; were present in the early days of the Radiophysics Laboratory and they were present for me and I have tried to continue them in my own areas.

I always tried to teach with a combination of a "physical understanding" approach and a more formal analytical approach. I carried this across into the research arena and in the way I operated in Radiophysics, I've seen it carried on by those I taught.

And so for the future. Are we teaching and mentoring a new generation who will have the capacity for thinking?

9. The Era of the Antikythera Mechanism.

The environments I have described must have existed in various places in the ancient world.

In the era before printed books, places like the Library of Alexandria must have played a critical role in the dissemination of the knowledge of the time. Something like the Antikythera mechanism was not the product of an individual working in isolation. The range of knowledge and crafts behind this was considerable. The coordination must also have been remarkable.

Let's look at the background scientific achievements of the era in Fig 3.

Thales of Miletus. ~585 BCE	Predicted solar eclipse 28 May 585BC
Aristarchus of Samos 310-230 BCE	Deduced that the Sun was larger than Earth and that it's the Earth that's moving
Eratosthenes of Cyrene 275-192 BCE	Method to calculate prime numbers Calculated circumference of the Earth
Hipparchus of Nicaea 162-128 BCE	Discovered precession of the Earth Calculated the distance of the moon
Antikythera designer ~100 BCE?	Integrated understanding of work of Thales, Aristarchus, Eratosthenes and Hipparchus, levers and waterwheels into a new mechanism?

Fig 3. The Ancients Background Science

If we look at the timelines in Fig 4, we see that there was substantial background learning at the time.

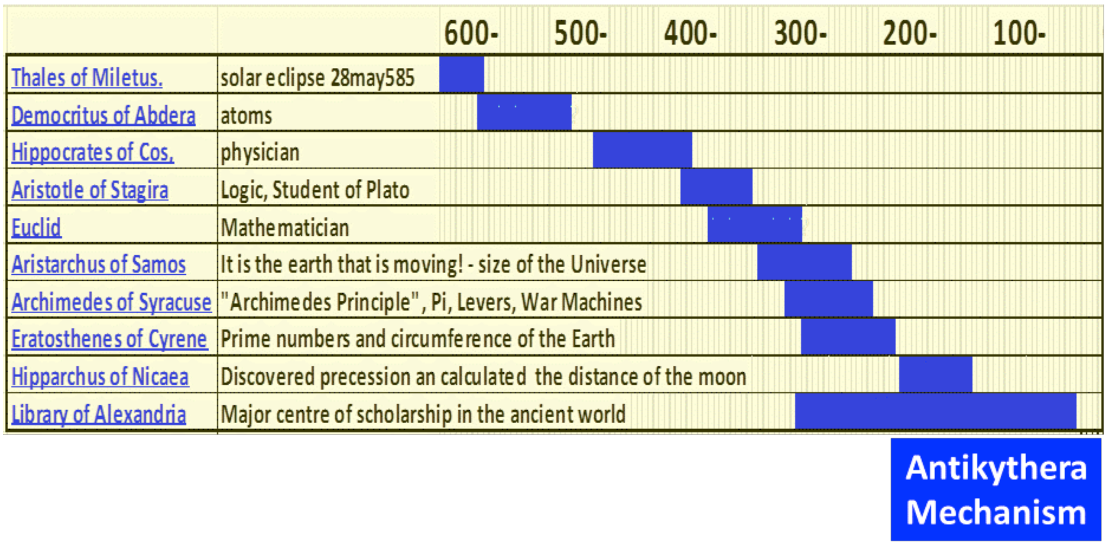

Fig 4. The Ancients Timeline

Many of the ingredients for success were clearly there at the time and one is left with the question: Who was the champion who brought this project together?

10. What are the lessons?

My mentors and their mentors had the capacity to hold and manipulate a complex image and a concept in their head. They were "System thinkers". They had the authority to implement decisions flowing from their deliberations on these concepts and were not blocked by people who were unable to grasp the broader issues.

The Antikythera Mechanism is surely an example of this! Such a mechanism doesn't arise without the supporting elements.

The Radiophysics environment and those following from it were excellent ones for allowing new ideas to blossom. Similar situations existed in many other places – other RA groups, Bell labs etc. Something similar must have existed for the Antikythera mechanism to be developed.

I always tried to teach with a combination of a "physical understanding" approach and a more formal analytical approach. I carried this across into the research arena and in the way I operated in Radiophysics, I've seen it carried on by those I taught.

And for the future:

> Are we working to ensure such environments exist in the future?
>
> Are we identifying and developing the next generation of "system thinkers"?
>
> Are we protecting our system thinkers of the future in an increasingly bureaucratic world?

THAT is our challenge!

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