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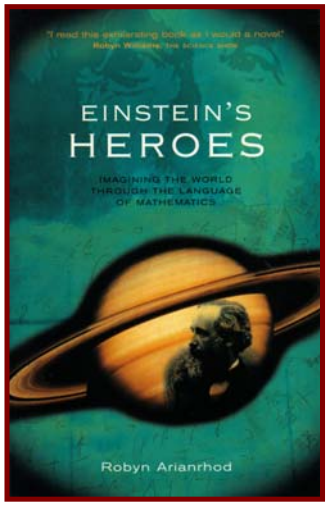
EINSTEIN'S HEROES
Robyn Arianrhod



Teachers' Notes
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ISBN: 978 07022 3408 8 / AU$26.95

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University of Queensland Press
ABN 63 942 912 684

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YOUR EXPECTATIONS

Every reader comes to a text with an understanding of what they expect from it. This can be determined by your previous knowledge of a writer's work from critical reception such as reviews or popular media coverage. Or by the fact that (in the case of *Einstein's Heroes)* you know that it is a work about mathematics … since it's sub-titled 'Imagining the world through the language of mathematics'. Consider these points as you read and discuss this work of nonfiction. **Critical literacy** depends on an understanding of the conventions of a text and the notions and expectations we bring to it as a reader.

- The cover design features a portrait of James Clerk Maxwell, an image depicting a planet, and a quote from Robyn Williams the science broadcaster. The back cover blurb describes the text. What does the front cover text, and back cover blurb lead you to expect from this work?
- Read the Author's Note on the preliminary page as well.
  What does the title seem to suggest? Before reading the text, consider your own attitude to the subject, and then examine how that attitude has changed after you've read the text.

SUMMARY OF THE TEXT

'Real mathematical skill is linguistic and imaginative rather than arithmetical; mathematics is a language for thinking dramatic new thoughts, not merely for doing accurate book-keeping.' (p 96)

Einstein's Heroes is inspired by the author's love for the prophetic capacities of the language of mathematics 'to describe things we cannot see or even imagine'. The tone of Arianrhod's approach is strikingly established in the opening paragraph in which she refers not to a mathematics textbook but to David Malouf's novel *Remembering Babylon* as an example of how language can conjure up landscapes rather than being simply a descriptive instrument. So, too, she suggests, physicists' use of the language of mathematics has demonstrated many times, in vastly different decades and contexts, that it also has the capacity to conjure up physical reality. Arianrhod regrets that often schooling cements the notion that maths is a pragmatic instrument rather than one which can imagine the fantastic possibilities of the universe. This work challenges this false premise in celebrating the magic of mathematics.

In focusing on language this work explores the lives of three men who inspired Albert Einstein (1879-1955) – primarily James Clerk Maxwell (1831-1879), but also Michael Faraday (1791-1867) and Isaac Newton (1642- 1727), and how

they and several others refined the usage of that language. It details the aspects of their lives which contributed to the men they became, and how that influenced their discoveries. It ultimately uses biography as a method by which to trace a growing understanding that *'When Galileo and Newton used mathematics*

as the language of physics, they used it as a tool – a servant of physics. In Maxwell's work, however, mathematics would become the 'queen of science', because his physics hinges on the fact that mathematics is a language in its own right.' (p 130)

This is in one sense a eulogy to Maxwell, to a genius who Arianrhod suggests has not entirely received his proper due. Running through the work is the author's immense admiration for Maxwell's humble achievements which were not only thwarted by colleagues in his own lifetime, but until recently not fully acknowledged by the international community, save for a band of devoted followers.

The central thesis here is that the language of mathematics is like ordinary language but with one key difference – *'one of precision'* (p 30). While ordinary language is especially good at expressing things qualitatively, and both languages can describe things quantitatively, the language of maths is much better at the latter. (pp 130-1)

Arianrhod makes a convincing case for this by demonstrating that *'Like ordinary language, it consists of definitions whose meanings have to be assimilated, and whose grammar provides a structure for ordered thinking and communication. It takes effort to learn these rules and definitions, but even our own native languages need continual work from us if they are to reveal their full richness.'* (p 131) She highlights the fact that ordinary language *'is about meaning while mathematics is about grammar, about structure, form and pattern.*' (p 146)

She also records the internationalism of mathematical language (p 138) and the origins of the usage of words in the history of science as a 'language' and how they are often related to facts that are no longer common knowledge. For example, she points out that *'In Maxwell's day, however, many scientists thought electricity was a kind of fluid – hence the electrical application of the terms 'current' and 'flow'* (p 23) and *'the word algebra comes from the Arabic 'al-jabr.'* (p 30) She traces the fascinating history of mathematical terms which were invented by thinkers like Maxwell who named the process of vector multiplication. Such terms have *'evolved like those in any human language, in a tentative, communal and often humourous process'* (pp 215). She relates the beauty of equations to the beauty of poetry and her example of Maxwell's

equation, compared to Blake's famous quatrain (pp 227-8), is a useful starting point for anyone requiring proof of this comparison.

Arianrhod also makes the link between science fiction and science in order to demonstrate that many of the scientific principles on which modern technology are based and which were first 'imagined' by mathematicians, were once thought fantastic. She cites for example, radio waves (p 5) which made not only radios but television and mobile phones a possibility.

Another fascinating aspect of this work is the concept that science might be actively thwarted by religion or conservatism. She shows that the Greek era of mathematical discovery was ended *'in 529 AD, when the Byzantine emperor Justinian closed down the 'pagan' Greek-speaking philosophical academies.'* (p 168) Copernicus for example, and later Galileo, were ruled 'heretical' by Pope Paul V for daring to suggest that the sun and not the earth was at the centre of the cosmos (pp 53-5). It is hard to imagine, with the benefit of hindsight, that a great thinker such as Galileo was humiliatingly forced to deny his own scientific belief and to *'refrain from all teaching and other public scientific activities'* (p 55).

It is also interesting to read of Maxwell's battles to win over his colleagues who wanted to cling to mechanical model-making rather than accepting Maxwell's new mathematical paradigm for doing theoretical physics. (pp 216-228)

Arianrhod challenges 'lazy' scientific thinking which accepts either traditional wisdom or scientific dogma at face value. This work describes the author's obvious joy in the parallels between the 'macrocosm' of the universe and the 'microcosm' of human lives which is intended to fill the reader with delight at the thought of the grandeur of the world's mysterious patterns. For example, the parallel made between the monthly cycles of women, and the moon's cycles (p 59) makes obvious sense but is based on quite complicated concepts derived from several sciences. The observation that humans love patterns because *'our own bodies are essentially symmetrical; or because we needed to learn to recognise the rhythms of the seasons in order to plan the gathering or agricultural activities that provide our food.'* (p 137) is used as further justification for the essential relevance of mathematical patterns in language to our lives.

Similarly the Pythagoreans pioneering work in *'the mathematical physics of music'* (p 148) is linked to Newton's whimsical notion that gravity might be *'simply a manifestation of the ancient and beautiful idea of cosmic harmony* (p 149). And we are reminded that Eratosthenes estimated '*the distance around the circumference of the earth'* (p 157) by applying his knowledge of the geometry of angles!

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Finally, Arianrhod suggests that Maxwell's equations have had longevity because they had such far-reaching applicability *'from the subatomic to the galactic. The microcosm united with the cosmos.*' (p 279)

This book makes a persuasive case for the need to recognise the links between mathematics, science and the arts in a well-rounded intellectual life. Arianrhod

is clearly as much a philosopher and student of language and literature, as she is a mathematician, just as her 'hero', Maxwell was, as well.

MATTERS OF STYLE

This work is a blend of science, history, biography and philosophy.
Arianrhod moves from mathematical explanations to biographical history in a challenging fashion. In using such a multi-disciplinary approach does Arianrhod make this a more informative and interesting work than it would have been, had she used a strictly one-dimensional scientific approach? Did you find the mixture of biography and science disconcerting or illuminating? Discuss.

Arianrhod is what is termed a 'literary science writer'. Her skill lies in making complex ideas and concepts understandable even to those who are not familiar with them. It is based on a combination of scientific and mathematical knowledge, creative writing skills and philosophy. She infuses non-fiction with the sense of wonderment we often associate with reading fiction. For example, read the chapter 'A Reluctant Revolutionary' (pp 8-13) which details James Clerk Maxwell's childhood and his extraordinary discovery of a mathematical theory at fourteen.

Does non-fiction writing often fail to invest reality with the sense of imagination it deserves? Research the work of other such writers in the past e.g. D'Arcy Wentworth Thompson (mentioned on p 132). Read current science writing by people such as Robyn Williams or by investigating texts in (for example) medical journals and newsletters.

Research the prospects and skills required for working as a technical, medical or science writer. You might also explore websites such as Australian Science Communicators Available: http://www.asc.asn.au/ [Accessed 1 February 2005] which lists course and conferences and frequently asked questions about science writing. See also: Australasian Medical Writers Association of Australia. Available:
http://www.medicalwriters.org/pub.asp?page=Home&pubid=1&issid=1www.
[Accessed 1 February 2005]
Read what Maxwell wrote about 'good' science writing (quoted p 200). Then write your own piece of science writing based on some idea which interests you.

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This book points out the similarities between textual and mathematical languages**.** Read for example, the discussion of puns and analogies (pp 91-2) or 'the grammar' of numerical relationships (pp 136-7) or her suggestion that *'algebra is like poetry. Both get to the essence of things, in an elegant, economical way.'* (p 176) The language of mathematics is used often in this book to demonstrate scientific theories such as gravity. How good are you at interpreting this language? Do we use this language too infrequently in every day life, in your opinion? Do you agree that mathematics is a language?
Discuss the implications of her arguments.

QUESTIONS TO DISCUSS WHILE READING IN SMALL GROUPS

- The failure to understand or appreciate mathematics is a failure, not so much of the intellect, but of the imagination. Discuss.
- Read the author's description of the similarity in the process of describing things via both linguistic and mathematical definitions (pp 132-3). Discuss some of the examples she uses.
- What was the fact which you discovered in this book, which intrigued you the most?
- Scientists are rarely acknowledged as 'heroes' unlike sports stars and people in entertainment. Discuss the meaning and derivation of the word 'hero'. Relate that finding to the people described in this book. Did you find them and their discoveries heroic? Why do we usually employ the word 'heroic' in such a narrow fashion? Research and read about the Australian Science Communicators' award to *Unsung Heroes*.
- Another fascinating aspect of the discoveries documented here is the way in which scientists and mathematicians were able to prove that 'earthly' phenomena were also visible in the entire cosmos. For example, Newton *'hypothesised that gravity is a universal force, not just an earthly one'* (p 52) which led to significant astronomical discoveries. The discovery of the planet Neptune was aided by mathematical calculations concerning the *'observed distortion of Uranus's orbit'.* (pp 25-6) Were you aware of the influences of different scientific disciplines on each other?
- Science is a process of disproving 'popularly-held' beliefs or presumptions by questioning their fundamental premises using mathematics and other disciplines to 'test' their validity. Discuss.
- Just as some sciences have taken generations to become accepted, conversely we often deny the validity of ancient arts which have gradually become discredited by their inaccurate or opportunistic usage. Astrology is a science which had significant effects on the theories of thinkers such as Kepler, Copernicus and Newton (p 60) but today, because of its appropriation by popular media, it does not attract the same academic recognition. Discuss.

- *'A successful theory is logically consistent, philosophically satisfying and sufficiently physically accurate over a wide range of situations to provide new insights about the physical world. It does not have to be completely accurate, and it does not have to provide the last word on reality.'* (p 75) What part of this definition do you agree/disagree with?
- Hooke *'was a much better experimentalist than theorist'* (p 78). Which of the two would you prefer to be?
- '*While physics has replaced philosophy as the primary source of information about physical reality, philosophy still has an important role to play in analyzing the way we perceive and describe reality. So much so that physics was called 'natural philosophy' until the end of the nineteenth century.' (*p 87) Discuss the relationship between physics and philosophy.
- *'Physicists tend to assume that the simpler of two alternative theories about nature is more likely to be the correct one, other things being equal.'* (p 127) Discuss this in relation to any discovery detailed in this book.
- The conflict between religion and science (p 89) arises because theoretical analysis often challenges traditional belief. It is a question of power and of how religious certainty is often threatened by new ideas. Discuss.
- Arianrhod raises the question of 'stereotypes' regarding scientists (p 97) in countering the idea that they are 'solitary geniuses' working in isolation, suggesting that instead people like Maxwell shared their ideas and further developed the discoveries of their mentors. She also shows that 'ownership of ideas is often hotly contested particularly where those ideas had a commercial application such as the long-distance wireless telegraphy commonly attributed to Marconi (p 239) and the telephone attributed to Alexander Graham Bell which sparked ongoing litigation (p 267). This same stereotype of 'solitary genius' has been applied to writers and other artists. Why do we harbour the notion that great thinkers and creators must be solitary beings? Discuss.
- The book suggests that Maxwell *'gave his ideas freely to the world'* (p 247) achieving greatness but not the public accolades he deserved. He wasn't interested in fame, as his peer Thomson (who was elevated to the peerage, but was also a great scientist) was. Does modern society value fame and commercial success too much? Are popular, commercial and scientific success mutually exclusive?

QUESTIONS FOR REFLECTION AFTER READING

Einstein's Heroes is relevant to a range of Curriculum Areas observed throughout Australia, and is useful not only in the application of mathematical concepts but to many other disciplines.

With regard to mathematics, it enhances the student's appreciation of and attitudes to mathematics, by challenging and enriching a student's understanding of the relevance of mathematics and encouraging cross-disciplinary research. Read the Chapter 'Mathematics as Language' (pp 130-171). This might prove a useful guide to your students' studies before embarking on the teaching of algebra, calculus, and geometry. It also encompasses key learning areas such as mathematical inquiry, choosing and using mathematics, learning to use ideas about number, space, measurement and chance, and mathematical ways of representing patterns and relationships to describe, interpret and reason about their social and physical world. It shows that mathematics plays a key role in the development of students' numeracy and assists learning across the curriculum - but more - that it is an important tool with which to understand the world around them.

- What is the relationship between electro-magnetic 'fields', 'vector calculus', and analytic geometry?
- What discoveries have been made by mathematicians since Maxwell's discoveries changed the face of this discipline?
- Read the description of vector multiplication (pp 210-3) and follow the steps described to demonstrate it.
- Read the Appendix (pp 282-3) and follow the steps outlined to prove that E=√2 is irrational, and discuss your findings. What do you understand by the Theory of Relativity or $E=mc^2$ (pp 134-5)?

Study of Society

- The influence of Pope Urban over Galileo's life is a tragic example of how innovation is often thwarted by extreme conservatism. Is such power still evident in today's society? Are Australian scientists being denied the necessary support to bring their discoveries to public attention?
- Research or read about a current scientific hypothesis or development and discuss.
- This work documents the tangible social and political power of scientific discovery in reporting that when *The Times* was able to telegraphically report on the horrors of the Crimean war *'public opinion in Britain turned against the war, which ended in early 1856.'* (p 106) 250 years later the media has unimagined capacities to report on war, and yet we see very little of the casualties and the atrocities occurring in many sites including Afghanistan and Iraq. Discuss.
- Arianrhod refers to the exclusion of women in the 19th century from the study of science (p 88) and her book is about the achievements of men. Read about and research the achievements of women such as Marie Curie, *'who coined the term radioactivity in 1898'* (p 135) during this period, despite the institutional prejudices against them. Read Sue Woolfe's *The Secret Cure* (2003) which is a novel which explores these

issues and the role of Rosalind Franklin in the discovery of DNA. Are women in science still threatened today by such attitudes? Read: Where are the Women in Australian Science? A University of Melbourne website
Available:
http://www.austehc.unimelb.edu.au/wisa/
[Accessed 22 January 2005]
What barriers do you imagine you might face in pursuing the profession?

English

From your reading of the chapters 'Electromagnetic Controversy' and 'Maxwell's Mathematical Language', comment on the book's assumption that 'Physics is a discipline requiring the elegant and clever use of language, just as is literature.'

Arianrhod compares the structure of Maxwell's equations (p 227) to a Blake quatrain (p 228). She also says that 'like poetry, mathematics gets to the essence of things in an elegant and economic manner.' Discuss the relationship between poetry and mathematics.

Maxwell is a recognised poet (See Representative Poetry Online
Available:
http://eir.library.utoronto.ca/rpo/display/indexpoet.html
[Accessed 7 February 2005].
Discuss Maxwell's poetry and the insight it gives you into the life and work of a Victorian man. Compare his satirical verses (p 85, 93-4) with his emotional ones (p 103, 105).

'The language of maths has both enormous similarities and also differences to ordinary language and to poetry and literature in that it relies on patterns and is also the language of our culture's creation story, and of the stories physicists weave about the nature of reality. Who can really comprehend 4-dimensional space time or 11-dimensional strings or the Big Bang or Quantum Leaps? Work on a class unit which analyses poetry in terms of mathematical language, or discusses creation stories with the idea of maths as a framework.

Mathematics in Literature might be explored as a theme in the English curriculum. Arianrhod refers to Malouf (1993) and Woolfe (1996), and there are other literary works which relate to maths concepts. Refer to Alex Kasman's list 'Mathematical Fiction'
Available:
http://math.cofc.edu/faculty/kasman/MATHFICT/search.php?orderby=title&go=yes&medium=nv
[Accessed 1 February 2005

Read Brett Stevens' article 'Mathematics and Literature: Cross Fertilization' Available:
http:// http://www.pims.math.ca/pi/issue2/stevens.pdf
[Accessed 1 February 2005]
Some of the works listed in this article are included in the bibliography below, to provide further references. Read these novels or plays, which explore the ideas in this work and compare and contrast them.

Science Fiction has often been said to have 'predicted' things which have later been proven by scientists or mathematicians. e.g. Madeleine L'Engle's classic children's book *A Wrinkle in Time* (1973) predated the discovery of 'wrinkles' *'in the temperature of the primordial background radiation' … by a team of physicists led by George Smoot'* (p 190) of NASA in 1992 which led to the publication of Smoot and Davidson's *Wrinkles in Time* (1993)! Other novels or films were ahead of their time in this regard. Science Fiction also often irreverently satirises such discovery too. e.g. Douglas Adams' *A Hitchhiker's Guide To the Galaxy* (and sequels) contain a running joke that the answer to the secret of the universe is 42, sending up the quest by scientists to reconcile quantum mechanics and relativity. Some sci-fi writers have also had real scientific insight, like Jules Verne, Isaac Asimov and Carl Sagan, and have done some profound conceptual thinking. However Arianrhod's book is not so much equating maths with the wild imaginings of sci-fi but is about the power of maths to be truly prescient in the sense that where sci-fi writers often 'imagine' things which are later proved correct, the power of maths is that it enables scientists to imagine equally fantastic ideas, and it also provides a blueprint for actually testing these ideas and revealing unexpected new aspects of reality. Discuss.

Conduct a class debate by referring to some of the statements in this book, or by referring to websites containing quotations about mathematics as your starting point. E.g. Einstein once wrote that 'As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality.' Albert Einstein (1879-1955) Or: 'Philosophy is a game with objectives and no rules. Mathematics is a game with rules and no objectives.' (Anonymous) Or: 'Mathematics, rightly viewed, possess not only truth, but supreme beauty - a beauty cold and austere, like that of sculpture.' Bertrand Russell (1872-1970)

History

Maths has always been a *'global activity'* (p 139)—to make maths is as human as to make music or to tell stories—it can be examined in terms of its impact throughout history in many different cultures. Arianrhod outlines the *'main players in the history of mathematics'* (p 138) and later gives a précis of the contributions of the Greeks, Indian, China and the Middle East (pp 148-171)

leading to the post-Renaissance European or western domination of science. Research the history of maths and the contributions made by different cultures to its language.

Accidents of history have been influential in the progress of science as well. How have wars for example, impeded or enhanced scientific endeavours? This work suggests that *'The 'Golden Age' of Greek mathematics came to an end in 212BC, when Archimedes, deep in the middle of some mathematical calculations, was killed by a Roman soldier.'* (p 167) Modern conflicts have also demanded sophisticated arms which has driven the production of many new technologies. Premature deaths such as Maxwell's at 48 (p 270-3) also could be said to have changed the course of a discipline. Discuss.

History shows that often relatively new ideas had already appeared long ago, in a different form or discipline, although they were not proven at that time. For example, how does the 'Big Bang' theory compare with the work of early philosophers such as St Augustine and the creation myths which also 'seemed' to predict it"? (See pp 185-7)

Sciences

Scientific reality has been as important to people throughout the ages as have other kinds of reality such as literary or artistic imagination, or psychological archetypes and myths. Today it's indisputable that mathematical science is the basis of our modern lives—turning on a light, operating forms of microtechnology such as computers, cars, or mobile phones, or an appliance with an electrical motor. Discuss the revolutionary aspects of such scientific innovations, and the role that maths has played in enhancing our lives.

Scientific enquiry has not only practical applications but also social ones. Discuss the social implications of other discoveries explained in this book, and further discoveries which have occurred since, such as cloning. What has maths contributed to these discoveries? (Read pp 276-7 which describes the contribution made by maths to biological research.)

Science and maths have also sometimes had negative effects. Consider Einstein's devastated reaction to the fact that his equation was responsible for the dropping of the nuclear bomb on Hiroshima*. 'If I knew they were going to do this, I would have become a shoemaker instead of a physicist.'* (p 136) Discuss such regrettable results of mathematical discoveries.

At the end of the book it's suggested that *'physicists are still hoping to find the unified 'theory of everything'. To combine quantum mechanics not only with electromagnetism and special relativity (as in QED), but also with general*

relativity.' (p 280) Discuss this concept and clarify it by writing your own summary of the dilemma which is confronted by scientists in this regard.
In the early 1990s Stephen Hawking's book *A Brief History of Time* had huge popular impact on how we view physics. Is there any comparable work achieving similar impact today?

Media Studies
What is the media's role in making Newton and Einstein icons even in their own time, while Maxwell remains unknown, (as do others), despite the fact that he is an equal founder of classical mathematical physics along with Newton and Einstein? Read for example, this recent article: 'Einstein's Quantum Leap.' *The Australian, Higher Education* Wednesday 2 February 2005, p 30-1. Assess the coverage of the issues and personality of Einstein in this article.

Is it healthy to make superstars of scientists? Does it hinder or help science? Einstein for example has suffered from the 'tall poppy syndrome' leading detractors to accuse him of plagiarism. Tim Flannery, Australian celebrity scientist, has also been involved in some very public 'stoushes'. Does the media's willingness to destroy such 'heroes' allow ignorance to flourish and enable the propagation of false accusations based on incomplete knowledge? Discuss.

Faraday was idolised on the London speaking circuit in his day. Where are/ who are the Faradays of modern science?

Read widely and assess what sort of general treatment maths is given in the media. Arianrhod's book aims to correct stereotypes and to acquaint her reader with the real nature of mathematics. How prevalent are these stereotypes (outlined in **Questions to Discuss While Reading in Small Groups** above) such as 'solitary geniuses', 'men dominate the field'; 'maths is boring' etc.

Keep a file of print and digital media coverage regarding mathematical concepts, significant scientific figures or new theories. How much unintended misinformation is conveyed by the fact that maths like any subject is often subjected to the 'three minute grab' or to treatment of current new releases in a brief interview as is exemplified by for example, The ABC's Science Show which ran an interview by host Robyn Williams with three writers of new works on mathematics on 18/11/00.
Available:
http:// www.abc.net.au/rn/science/ss/stories/s212670.htm
[Accessed 2 February 2005]

How much does such a discussion really inform an audience unfamiliar with maths as a discipline?

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CREATIVE AND PERSONAL WRITING

Use the text to explore writing in a number of genres suggested by it:

Choose any chapter title and write an essay based on the information in that chapter, adding some new insights of your own.

Choose any genre to write on the theme of mathematics – short story (crime, thriller, romance, etc), poem, biography, etc.

On p 273 the text of a slogan printed on a university tee-shirt (which is a witty tribute to Maxwell's influence on mathematical language), is reproduced. Make up your own slogan referring to any of the concepts explored in this book.

SUGGESTED RESEARCH PROJECT(S)

Einstein's Heroes is a work which is a tantalising collection of facts, people and stories. Choose a person and the discovery associated with him, and using this work as a framework, also read more, beginning with the **Notes and Sources** (pp 284-306) and the **Bibliography** (pp 307-315) listed at the end. You might also gain a brief biographical introduction to the scientists who are covered here by referring to *Scienceworld Wolfram Research*
Available:
http://scienceworld/wolfram.com/biography/
[Accessed 13 January 2005]
Also choose other media pieces and use them in class as material for related discussions, reports and displays.

Research the life of a person featured in *Einstein's Heroes* in relation to a specific mathematical or scientific discovery, and present a project in any format you prefer. e.g. Display, video, playscript, report, website, illustrated picture book, or other medium to be discussed with your teacher. NB. Ensure that the work demonstrates the 'beauty and magic' of the language of mathematics in some way.
OR
Arianrhod believes that maths is as fundamentally human as art and music, and literature, where pattern is also important. (For example, think of the role of repetition in rhyme and folk tale, and of the use of repeated numerical sequences, in cumulative story-telling.) Explore this idea in as creative a way as possible.

ABOUT THE AUTHOR

Dr Robyn Arianrhod is a writer and mathematician whose passion for both literature and mathematics reflects her love of language. She lives in the foothills outside Melbourne, teaches mathematics at Monash University and

Monash International College, and her field of research includes the analysis of Einstein's equations of gravity and Maxwell's equations of electromagnetism.

ADDITIONAL READING

There is substantial reference material included in **Notes and Sources** (pp 284-306) and the **Bibliography** (pp 307-315) at the back of the book. The following includes texts and websites referred to in these notes.

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