



**“The book’s science is solid and McCarthy’s fervor genuinely infectious.  
The future never felt so close.” --- *WIRED***

**LEVITATING CHAIRS, QUANTUM MIRAGES,  
AND THE INFINITE WEIRDNESS OF  
PROGRAMMABLE ATOMS**



**WIL MCCARTHY**

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Additional information on the technologies described in this work can be found through The Programmable Matter Corporation, <http://www.programmablemater.com>.

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## Citations

**An Alternate Selection of the Library of Science Book Club  
An Alternate Selection of the Science Fiction Book Club  
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A Selection of How-To Media (aka Science News Books)  
Nanotechnology Now "Best of 2003"  
Amazon.com #4 Bestseller**

## Reviews

**"When he experimented with lightning, Ben Franklin mused that electricity 'might someday prove of use.' Now comes Wil McCarthy, offering a peek at something so potentially transforming, our grandchildren may build civilizations around it. If even a few of these possibilities come true, you'll always remember you heard it here first." -- David Brin, author of *The Transparent Society***

**"Programmable substances and futuristic computers will revolutionize our lives and allow us to soar beyond the limits of our intuition. No book better describes the impact of hypercomputing and the dazzling wealth of new materials coming our way than *Hacking Matter*." -- Clifford A. Pickover, author of *The Mathematics of Oz***

**"A grand tour of cutting-edge research: alchemy, 21st century style. The author makes an informative case for the promising, even magical, potential of programmable atoms." -- Publishers Weekly**

**"McCarthy effectively conveys the inherent gee-whiz character of his subject. A fascinating glimpse of research that may in a few years find its way into our everyday lives." --Kirkus Reviews**

**"[T]he book's science is solid and McCarthy's fervor genuinely infectious. The future never felt so close." -- Jennifer Kahn, WIRED**

**"McCarthy blends lucid nuts-and-bolts explanations of 'quantum dots' and other developing technologies with healthy doses of 'You ain't seen nothin' yet' descriptions of speculative applications. A fascinating book for any reader intrigued by new technologies." -- Barnes and Noble**

**"Promises to create a thunderclap of change. McCarthy takes a fantastical concept, coolly explaining it in a plausible way, and helps even the most science-deficient reader to understand how 'hacking matter' works, and what it means for all of us." -- Dallas Morning News**

**"Through the works of aerospace-engineer-turned-science-fiction-author Wil McCarthy... the promise of programmable matter could make the technology revolution wrought by semiconductors to date look like a warm-up for the main act. " -- Stephen Cass, IEEE Spectrum**

**"An excellent guide to some cutting-edge science. McCarthy has now joined the league of major writers like Asimov and Clarke who are comfortable writing both science fiction and science fact." -- Fred Cleaver, The Denver Post**

**"Veteran science fiction writer Wil McCarthy explores a frontier of real-world possibilities that could make all previous technological revolutions look like artifacts from the stone age. He has a knack for expounding hard science in layman's terms, [and] speculates enthusiastically on the potential benefits. " -- David Colterjohn, San Francisco Chronicle**

**"McCarthy employs a soothing narrative manner that draws reads into the story; even when the science gets tough to digest, there's enough freewheeling speculation to keep you going. Throughout, McCarthy describes the phenomenon of programmable matter as a kind of magic. His knack for describing it is magical in itself." -- Booklist**

**"*Excellent.* there's a sense that he's onto something *really* important -- the kind of thing that scientists and science fiction writers will be exploring for decades to come." -- Cory Doctorow, Boinboing.net**

# **HACKING MATTER**

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This book's prologue first appeared, in slightly different form, as an essay in NATURE. Other chapters are derived in part from material first published in WIRED, Analog, Science Fiction Weekly, Science Fiction Age, and assorted other magazines and Internet sites.

This book is also available in both hardcover format (Basic Books, first published in 2003) and as a paperback (Basic Books, first published in 2004).

Also by Wil McCarthy

*To Crush the Moon*

*Lost in Transmission*

*The Wellstone*

*The Collapsium*

*Bloom*

*Murder in the Solid State*

*The Fall of Sirius*

*Flies from the Amber*

*Aggressor Six*



# HACKING MATTER



**Levitating Chairs, Quantum Mirages,**

**and the *Infinite Weirdness* of**

**PROGRAMMABLE ATOMS**



**WIL MCCARTHY**



[wil@programmablematter.com](mailto:wil@programmablematter.com)

To Michael and Evalyn McCarthy,  
for making me curious



We're always looking for new physics;  
new behavior that has never been seen  
before. Once we find it, of course, we  
start to daydream.

----- M A R C K A S T N E R



JULY 4TH, 2100

## PROGRAMMABLE MATTER: A RETROSPECTIVE

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**THE FLICK OF A SWITCH:** a wall becomes a window becomes a hologram generator. Any chair becomes a hypercomputer, any rooftop a power or waste treatment plant. We scarcely notice; programmable matter pervades our homes, our workplaces, our vehicles and environments. There isn't a city on Earth -- or Mars, for that matter -- that isn't clothed in the stuff from head to toe. But though we rarely stop to consider it, the bones of these cities -- their streets, their sewers, the hearts of their telecom networks -- were laid out in a time when the properties of matter were dictated exclusively by mother nature.

Just imagine: if specific mechanical or electrical properties were desired, one first had to hire miners to extract appropriate elements from the Earth, then chemists and metallurgists to mix precise proportions under precise conditions, then artisans to craft the resulting materials into components, and assemble the components into products that could then be transported to the location of desired use. The inconvenience must have been staggering.


In the 22nd century, of course, any competent designer will simply define the shape and properties she requires -- including "unnatural" traits like superreflectance, refraction matching (invisibility), and electromagnetically reinforced atomic bonds -- then distribute the configuration file to any interested users. But prior to the invention of wellstone -- the earliest form of programmable matter -- this would have sounded like purest fantasy. With this in mind, we'll look back on the invention upon which, arguably, our entire modern civilization rests.

Consider silicon, whose oxide is the primary component of rock -- literally the commonest material on Earth. Humans had been making hammers and axes and millstones out of it for millions of years, but as it happens, silicon is also a semiconductor -- a material capable of conducting electrons only within a narrow energy band.




While invaluable in the development of 20th century digital electronics, silicon's "killer app" eventually proved to be as a storage medium for electrons. The layering of doped silica in particular ways can trap conduction electrons in a membrane so thin that from one face to the other, their behavior as tiny quantum wave packets takes precedence over their behavior as particles. This is called a "quantum well." From there, confining the electrons along a second dimension produces a "quantum wire," and finally, with three dimensions, a "quantum dot."

The unique trait of a quantum dot, as opposed to any other electronic component, is that the electrons trapped in it will arrange themselves as though they were part of an atom, even though there's no atomic nucleus for them to surround. Which atom they emulate depends on the number of electrons and the exact geometry of the wells that confine them, and in fact where a normal atom is spherical, such "designer atoms" can be fashioned into cubes or tetrahedrons or any other shape, and filled with vastly more electrons than any real nucleus could support, to produce "atoms" with properties that simply don't occur in nature.



Significantly, the quantum dots needn't be part of the physical structure of the semiconductor; they can be maintained just above it through a careful balancing of electrical charges. In fact, this is the preferred method, since it permits the dots' characteristics to be adjusted without any physical modification of the substrate.



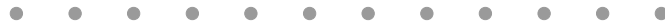
Who "invented" wellstone remains a matter of confusion and debate; similar work was being performed in parallel, in laboratories all over the world. Regardless of where the idea originates, the concept itself is deceptively simple: a lattice of crystalline silicon, superfine threads much thinner than a human hair, crisscrossing to form a translucent structure with roughly the density of polyethylene. It behaves fundamentally as a semiconductor, except that with the application of electrical currents, its structure can be filled with "atoms" of any desired species, producing a virtual substance with the mass of diffuse silicon, but the chemical, physical, and electrical properties of some new, hybrid material.

Wellstone iron, for example, is weaker than its natural counterpart, less conductive and ferromagnetic, basically less iron-like, and if you bash it over and over with a golf club it will gradually lose any resemblance, reverting to shattered

silicon and empty space. On the other hand, it's feather-light, wholly rustproof, and changeable at the flick of a bit into zinc, rubidium, or even otherwise-impossible substances like impervium, the toughest superreflector known.

Of the changes wrought by programmable matter in the past hundred years, not all have been universally welcomed. In the grand Promethean tradition, wellstone places the power of creation and destruction squarely in human hands. Many have argued that far from making us strong, this power fosters a quiet corruption of spirit. Still, the fable of the three little pigs holds true -- not even the Luddites among us build their houses of straw or sticks when impervium is a free download.

## ACKNOWLEDGMENTS



**THIS BOOK IS THE END PRODUCT** of a long evolutionary chain of stories and articles, whose existence and worldly reception owe a great deal to their editors. In roughly chronological order, I'd like to thank Scott Edelman, Chris Schlupe, Simon Spanton, Henry Gee, David A. Truesdale, Anne Lesley Groell, Stanley Schmidt, Martha Baer, Chris Anderson, and Bill Frucht.

The basic ideas came about after I'd digested The Quantum Dot by Richard Turton and a related article by Ivars Peterson, and discussed them at considerable length with the esteemed doctors Gary E. Snyder and Richard M. Powers. All of the above are responsible for seriously diverting the course of my life. I'd also like to thank Kenneth M. Edwards of the Air Force Research Laboratory for becoming interested at exactly the right time.

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And of course none of this would exist at all without the scientists doing the research. The ones I've spoken with have been uniformly friendly and enthusiastic, and I've tried to do them justice here, with all due apologies to the dozens of other scientists whose fundamental contributions I've left out or overlooked. The enormous assistance of grad students and postdocs too often go unrecognized, so I'll also extend blanket thanks to Andrei Kogan, Myrna Vitasovic, Nikolai Zhitenev, Gleb Finkelsetin, Stuart Tessmer, and all the rest of you out there.

Any errors in this book should be blamed on entropy, which always increases no matter how hard we try.



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## Clarke's Law and the Need for Magic

O Nature, and O soul of man! how far beyond all utterance are your linked analogies!  
Not the smallest atom stirs or lives on matter, but has its cunning duplicate in mind.

-- HERMAN MELVILLE, MOBY DICK (1851)

THE HARDEST THING YOU CAN ASK THEM is how old they are. The question seems to rock them back, to give them pause. "I guess I'm 38," one of them tells me uncertainly. "I must be 54," another answers, after even longer deliberation. It's not that these men are slow, it's that they're physicists. And they're involved in a research area as promising as it is new and strange, so if they seem a little distracted, well, c'est la vie. Despite modesty and caution so deeply ingrained that it might well be genetic, they also project an air of barely contained excitement. They're building a magical future, and they know it.

Through the entirety of human history, from the moment the first stone was picked up and hurled at an attacking predator, our lives have been shaped and focused and empowered by our technology. Nature would have us naked and unprotected, scrabbling in the dirt for sustenance; we prefer to be clothed and warm, well nourished, and equipped with a variety of tools to shape and interact with the environment around us. Initially these tools were found objects: sticks and stones. Later, we began to shape them for specific purposes, and then to connect them in intricate ways. We progressed from tools -- static pieces of specialized matter -- to machines, which are tools that can change their shape, and convert energy from one form to another. Matter that works, so you don't have to. Soon, we were experimenting with abacuses, and with animated models of the heavens known as "orreries." These led directly to mechanical calculating machines, and eventually to designs for general-purpose computers -- matter that thinks. This idea no

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