ILS 251 – FALL 1993 – SYLLABUS

Prof. – Robert March *TA – Craig McConnell*

	Textbook:
PFP	*Physics for Poets (3rd Ed.)*, R. March, Chapters 7-18
	Articles in *Scientific American:*
QP	" Quantum Philosophy," John Horgan, July 1992, pp. 94-101
CO	"How Cosmology Became a Science," S.G. Brush, Aug. 1992, pp. 62-70
	"The Golden Age of Cosmology," Corey S. Powell, July 1992, pp. 17-22
$\star n - m$	Page reference to supplementary notes in this packet

Dates	*Lecture Topics*	*Readings*	*Discussion*
Sep 2	Newton's *predictable* world	$\star 6 - 7$	*no meeting*
Sep 7	Interference and other wave phenomena	PFP 7	get-acquainted
Sep 9	The Michelson-Morley experiment	PFP 8	
Sep 14	The Postulate of Relativity	PFP 9	Practice problems
Sep 16	Space-time (qualitative)		
Sep 21	Space-time (quantitative)	PFP 10	OPEN
Sep 23	....continued	$\star 8 - 9$	
Sep 28	$E = mc^2$	PFP 11	*Problem set 1*
Sep 30	The twin paradox	PFP 12	
Oct 5	The Principle of Equivalence		OPEN
Oct 7	The worldview of general relativity		
Oct 12	Black holes and the Big Bang	$\star 10 - 12$	Review for midterm exam
Oct 14	Chaos out of order	$\star 13 - 15$	
Oct 19	Are atoms "real?"	PFP 13	Discussion of midterm exam
Oct 21	**EXAM**		
Oct 26	Probing the atom	PFP14	OPEN
Oct 28	Planck, Einstein, and the quantum	PFP 15	
Nov 2	Bohr's flawed but succesful model	PFP 16	OPEN
Nov 4	De Broglie's "matter waves"	PFP 17	
Nov 9	Wave Mechanics		*Problem set 2*
Nov 11	The probability interpretation	PFP 18	
Nov 16	Uncertainty and "tunneling"		Interpreting the quantum theory
Nov 18	Schrödinger's Cat	QP	
Nov 23	The Pauli principle and chemistry	$\star 16$	*Thanksgiving*
Nov 30	Nuclear physics & astrophysics	$\star 17 - 18$	*Paper due*
Dec 2	The Cosmic Background	CO	
Dec 7	Reactors and nuclear weapons	$\star 19 - 22$	Review & Recapitulate
Dec 9	Technology in the "New World Order"	$\star 23 - 24$	
Dec 14	Final remarks – **TAKEHOME DUE**		

INFORMATION ABOUT THE COURSE

OFFICE HOURS – Your professor is **Bob March**. Office hours are held in 4289 Chamberlin Hall Tuesday and Wednesday from 1:30 to 3:30, or call **262-5947** for an appointment at another time. Your TA is **Craig McConnell**, who holds office hours on the Union Terrace Tuesday from 12:00 to 1:00 (in the Rathskeller in inclement weather) and in 4155 Helen C. White, Wednesday from 12:00 to 1:00, telephone **262-3999**.

EMAIL If you have an electronic mail account, it is a good way to communicate with us without playing "telephone tag." Our EMAIL (internet) addresses are:

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EXAMS – There will be an exam in the lecture hour on *Thursday October 22*, and a takehome exam due in the final lecture, Tuesday December 15. For the in-class exam, you may bring two sheets (four pages) of notes. A study guide will be distributed a week before, describing the exam in detail. You will have a full week for the takehome.

PROBLEMS – There are three problem sets on p. 4 of this syllabus. The "Practice Problems" will be discussed in class, but are not to be handed in. Problem sets 1 and 2 are due in discussion on the dates indicated on the schedule. *You may be called upon to work problems at the board on the due date.*

PAPER – Write a paper of length 7 to 14 pages, connecting a *concept* or *discovery* discussed in this course to something *outside* of natural science. The connection may be *conceptual* (show how they are related, analogous, or antagonistic), *historical* (discuss the science in its historical and cultural context), or *personal* (connect them through their impact on your own thinking). It will be judged for *creativity* more than for scholarship. *Due in discussion, December 2/3.* Abstracts of some excellent papers are given on the following page. A review of a book or article is acceptable, but it must be a *critical* review, one that takes and defends a stand on the validity of the author's position.

GRADING – Grades in this course are a *performance weighted* average of four scores: the two exams, the term paper, and a discussion grade based in part on the problem sets. The *best* score counts 40%, second best 30%, third 20%, worst 10% of your grade.

SOME UNITS, CONSTANTS, AND SYMBOLS

Quantity	*Symbol*	*Value*
speed of light:	**c**	3×10^8 m/s = 300,000 Km/s = 1 ft/nsec
electron-volt:	**eV**	1.6×10^{-19} joules
Planck constant	**h**	4.15×10^{-15} eV-seconds

PREFIXES FOR UNITS

prefix	*symbol*	*multiplier*	*prefix*	*symbol*	*multiplier*
kilo	K	10^3 (thousand)	milli	m	10^{-3} (thousandth)
mega	M	10^6 (million)	micro	μ	10^{-6} (millionth)
giga	G	10^9 (billion)	nano	n	10^{-9} (billionth)
tera	T	10^{12} (trillion)	pico	p	10^{-12} (trillionth)
peta	P	10^{15} (quadrillion)	femto	f	10^{-15} (quadrillionth)

SOME ABSTRACTS OF ILS 251 TERM PAPERS

(don't be intimidated – these were A^+ papers!)

"Sunday Morning" and the Uncertainty Relations — Compares the view of what it means to "know" the world that is implicit in a Wallace Stevens poem with that underlying the uncertainty relations. Finds them akin in their rejection of a knowable, fully-objective reality.

Einstein and Picasso — Examines parallels in the work of two contemporaneous "revolutionary" creative figures. Concludes each was responding to a perceived crisis in his field, and both resolved it by asserting the primacy of the human intellect and imagination in the creative process, and by the rejection of procedures and concepts justified by convention.

Einstein and the Vienna Circle — Shows how Einstein's early embrace and subsequent rejection of strict positivism parallels to some degree the evolution of the ideas of an influential group of philosophers.

Schrodinger's Cat Lives! — A peculiar, somewhat tounge-in-cheek interpretation of the quantum theory based on the philosophy of Dr. Pangloss in Voltaire's *Candide* (whatever happens is bound to be for the best) and the "many-worlds" interpretation of Everett, Wheeler, and Graham.

Quantum Logic — Outlines an attempt by several contemporary philosophers to interpret the quantum theory by developing a formal logic that allows intermediates between "true" and "false." Argues that while the problem is formally resolved, its disquieting features remain.

God and Science — A devout Orthodox Jew gives his reaction to modern science. Argues that it is an admirable exercise of the human intellect, but should be subordinate to the deeper truths revealed by faith and theological scholarship.

Time Travel and Parallel Universes — Resolves the paradoxes of time travel (of the kill-your-grandfather sort) by means of parallel universes. Illustrated by an amusing photomontage.

Pedal to the Metal in Space — Speculates about why science fiction writers seem determined to overcome the relativistic speed limit. Concludes it arises from a failure of the imagination. Gives a short sketch of a plot that *exploits* the limit.

Relativistic Cartoons — A rendering of several relativistic effects (the speed limit, Lorentz contraction, time dilation, curved spacetime), in amusing comic strips that are scientifically reasonable (and well drawn).

The Franck Petition — Recounts an attempt by some Manhattan District scientists to prevent the use of the bomb against Japanese civilians. Concludes the effort showed high ideals but a lack of understanding of the political realities. Maintains that given the circumstances the decision to use the bomb in this way was inevitable.

Review of "Subtle is the Lord" — A review of a biography of Einstein by Abraham Pais, a theoretical physicist. Analyzes the author's statements to discover what it is that a scientist lauds or disapproves of in the life and work of another scientist.

SCIENTIFIC NOTATION

In this course, we will often use very large or very small numbers that are awkward to express as decimals. For these we will need *scientific notation*, sometimes called "floating point". The power to which 10 is raised is called the *exponent.*

To convert ordinary decimals to scientific notation:

If the number is *greater than 1*, count the number of digits to the left of the decimal point. The exponent is *positive* and *one less than* the number of digits.

Examples: $2,450,000 = 2.45 \times 10^6$ $223.7 = 2.237 \times 10^2$

If the number is *less than 1*, count the number of *zeroes* to the right of the decimal point, until you reach the first non-zero digit. The exponent is *negative* and *one more than* the number of zeroes.

Examples: $0.00000076 = 7.6 \times 10^{-7}$ $0.234 = 2.34 \times 10^{-1}$

To multiply:

multiply the numbers and *add* the exponents

Example: $3.2 \times 10^{-3} \times 2 \times 10^{13} = 6.4 \times 10^{10}$

To divide:

divide the dividend by the divisor and *subtract* its exponent from that of the divisor.

Example: $2.5 \times 10^{-6}/2 \times 10^{-15} = 1.25 \times 10^{9}$

To move the decimal point:

for each place moved to the *left, add 1* to the exponent.

for each place moved to the *right, subtract 1* from the exponent.

Examples: $310 \times 10^{-10} = 3.1 \times 10^{-8}$ $.05 \times 10^5 = 5 \times 10^3$

To raise to a power:

raise the number to the power, and *multiply* the exponent by the power.

Examples: $(2 \times 10^5)^3 = 8 \times 10^{15}$ $\sqrt{2.5 \times 10^7} = 5 \times 10^3$

The second example, a *square root*, is the "1/2 power". The exponent was *odd*, so we must move the decimal point to make it even (25×10^6), in order that the final exponent be an integer.

To add or subtract:

by moving the decimal point, express both numbers with the *same* exponent. Then add or subtract, leaving the exponent *unchanged.*

Example: $5.67 \times 10^6 - 4.2 \times 10^5 = 5.67 \times 10^6 - 0.42 \times 10^6 = 5.25 \times 10^6$

PRACTICE PROBLEMS

for discussion Setember 16-17

(1) Calculate the following: (a) $150 \times 3 \times 10^5$; (b) $(8.4 \times 10^{-7}) \div (2.1 \times 10^4)$; (c) $\sqrt{3.6 \times 10^{-9}}$ (d) $1.75 \times 10^9 + 2.5 \times 10^8$

(2) Convert 100 MeV (million electron volts) to *joules* (see table on p.2 of this syllabus).

(3) How far does light travel in $\frac{1}{100}$ second?

(4) What is the ratio $\frac{v}{c}$ for a jet plane traveling 240 m/s?

PROBLEM SET 1

due September 30-October 1

(1) "100" on an FM radio dial stands for a frequency of 100 MHz (10^8 Hz). What is the *wavelength* of radio waves of this frequency?

(2) A Michelson interferometer uses light of wavelength 0.5 μm (micrometers). It produces a pattern of parallel straight fringes. Describe what happens to the pattern if one of the mirrors is moved by 3 μm.

(3) Calculate the "Lorentz factor" γ for a velocity $v = 0.3c$ *two ways:* (a) use the exact formula (top of p. 97 of your text); (b) use the approximate formula (bottom of p. 97). Comment on the appropriateness of using the second formula at this speed.

(4) Exercise 3 on p. 265 of your text.

(5) Write a *one-paragraph* explanation of the following comment: *"In relativity, the speed of light is no longer regarded as a property of light itself."*

PROBLEM SET 2

due November 11-12

(1) Green light has wavelength 0.5 μm. Calculate: (a) The frequency of this light; (b) the energy of one quantum of this light (you will need the value of h on p.2).

(2) In a *photoelectric* experiment, it is found that: (i) The lowest frequency of light that will work is 5×10^{14} Hz; (ii) Light of 9×10^{14} Hz ejects electrons with energies up to 1.68 electron volts. Calculate: (a) Planck's constant (the answer should be close to the value on p.2); (b) The energy required to remove an electron from the metal.

(3) In a hydrogen atom, it takes 13.6 eV of energy to remove an electron from the atom ($E_1 = 13.6$ eV). (a) How much energy does it take to raise it from the ground state to the first excited state ($n = 2$)? (b) When it drops back to the ground state, what is the *frequency* of the light emitted?

(4) Compare *special relativity* to the *Bohr model of hydrogen* from the point of view of: (a) logical self-consistency; (b) the uses made of experimental data in developing the theory.

WELCOME TO ILS 251

Any sensible person realizes that the world we live in is now, and has always been, a confusing and threatening place. The unexpected can happen at any time, and try as we can to keep the lid on, things often get out of hand. Science is motivated, in part, by the psychological necessity to feel less at the mercy of chance.

By contrast, the heavens seem a terribly orderly place. The sun and stars wheel majestically and reliably across the sky. The moon is a bit more complicated, and the planets a great deal so, but careful observation and mathematical analysis make even these motions predictable, years into the future.

The physical system developed in the seventeenth century by Isaac Newton, and refined for more than 200 years by his successors, purported to have discovered the laws underlying this order, and asserted that *the same laws applied equally well on earth!* The order that ruled the solar system was there on our planet, lurking beneath the confusion of day-to-day life. Newton had met Plato's challenge to "save the phenomena" by discovering the truer, hidden reality.

In the practical sphere, Newton's triumph held forth the promise that knowledge might make us the masters of our own destiny. This promise has been a central force in Western civilization ever since. Other branches of knowledge strove for the same predictability. Karl Marx claimed to have discovered inexorable laws of history, and Sigmund Freud believed he had uncovered the forces that shape human personality. Modern neoclassical economists formulate mathematical models that closely mirror Newtonian astrophysics in their mathematical form, but which are based on rather questionable assumptions about human behavior.

None of these theories has come close to matching Newton's triumph. Yet the faith of their adherents remains unshaken. A little better data, a faster computer, a few refinements in the equations — perfection lurks just beyond the horizon.

But Newton's own realm, the physical sciences, have been forced to abandon the faith in a wholly orderly, predictable underlying reality. It has been a gradual process, taking most of the twentieth century. This unraveling is a central theme of ILS 251.

The first blow — a seemingly innocent one — came from Albert Einstein's theory of Relativity. What it showed was that Newton's reality was *not unique*. A different underlying reality could explain everything Newton had equally well, and could explain or predict *new* phenomena. In later years Einstein came to recognize the significance of this discovery. It was that much of what we considered order *in nature* was really order *in our minds*. It represented conventions by which we organize our knowledge of things.

Still, Einstein never lost his faith that his science ultimately rested on a material world that existed independent of human knowledge, and that world was orderly and predictable. Indeed, his work had made some of Newton's predictions *more* accurate. Thus he rejected the next step in the unraveling of the Newtonian world-view — the final versions of the *Quantum Theory*.

In this theory, the behavior of individual atoms and their parts is dominated by pure chance. It also introduces the *observer* into the theory — nature observed is nature changed. The shock of this 65-year old discovery echoes in philosophical discussions to this day. Several books have been written, by reputable authors, claiming that physics has now left the tradition of Western philosophy and created a science that fits more harmoniously within Eastern (Taoist/Buddhist) thought.

Nonetheless, scientists could still find reassurance in the knowledge that everything big enough to see or touch is composed of countless numbers of atoms. However chaotic the world of the atom might be, these myriads of chance events will "average out," leaving our familiar everyday world as predictable as before. An orderly reality somehow rests on a deeper, chaotic foundation!

The final blow has come in the last two decades. Computers allow scientists to deal with more complicated situations than the old methods of pencil and paper would allow. They reveal that even if the underlying laws of nature are orderly, any prediction must still get less and less accurate with time. This is because we never know present conditions *exactly* — there is error in any measurement. When one moves away from the simplest cases, there are also causative factors that are neglected.

The study of pathological cases — where predictions of the future are so sensitive to small changes in our knowledge of the present that they go to hell in a great hurry — is now conducted under the name of "chaos studies."

Even Newton's orderly solar system is not as predictable as it seemed. Interestingly, Newton himself had suspected as much. But as a deeply religious man, he assumed that a benevolent Deity would step in and straighten out any residual disorder. Scientists are gradually coming to the realization that the orderly, predictable situations we have emphasized for the last few centuries are the exception, rather than the rule, in nature. We focussed on them because they were the only ones our limited mathematical tools would allow us to analyze. We comforted ourselves with the thought that they must therefore be more "fundamental."

In the same era in which scientists are becoming less confident about predicting the future, the social significance of their work has grown by leaps and bounds. Science is becoming more and more essential to the development of technology. Since World War II it has developed rapidly, with growing ties to industry, government, and the military. In the final segment of the course we will look into *nuclear energy* in its civilian and military applications as a case study of the workings of organized science, and its ties to the larger society.

Thus this course will start out with an exercise in highly abstract thought about fundamental underpinnings of reality. It will move into a more concrete world, that of the atom, in which the rules are radically different from those that apply on our ordinary scale of experience. Finally, it will deal with contemporary problems in their full social as well as technological context.

Another function of science in Western Civilization is to replace religion as the source of our "creation myths." 1992 was a banner year for cosmology, and this will be another theme for this year's course.

A CASE STUDY OF RELATIVISTIC TIME

This example is designed to show how it is possible for two people in motion relative to one another *each* to believe the *other's* clock is slow. The point is that any comparison of the clocks involves communications over distances that are both *large* and *changing*.

Two astronauts (Joe and Sue) pass one another in the far reaches of interstellar space, at a relative velocity of 0.6c. At the instant they flash by one another, they synchronize watches, and Sue agrees to send a radio message (which travels at the speed of light) in 10 minutes. The ensuing dialogue follows:

SUE– Ten minutes at the tone – ding!

JOE– Aha! – Just like Einstein said, you have the slow clock! If you'd *really* called back in 10 minutes, you'd have been 6 light minutes away, and I would have gotten your message in 10 plus 6 equals 16 minutes. I must sadly inform you that my clock read 20 at your ding. For your motion, gamma is 1.25. You really transmitted at 12.5 minutes, when you were 7.5 light minutes away. That adds up to 20, like I said.

SUE– Okay, knucklehead, reread your Einstein! Two can play at this game, and I can just as easily show that *your* clock is the slow one! I say *you're* moving, and were only six light minutes away when I sent. But you were running away from my message, which had to catch up at a relative speed of 0.4c. It took 15 minutes to make up your 6 light minute lead, so you really got it at 25 minutes. You say 20, so *yours* is the slow clock.

JOE– Oops! I guess I gotta concede that you know what *your clock said when you sent* – I know what *mine read when I received* – and these are the *only* facts we have to work with. We're arguing about what my clock read when you sent, or yours read when I received, which has nothing to do with actual experience, since we're hundreds of millions of miles apart!

SUE– Right you are! Isn't it odd how we *must disagree* on these calculations, *in order to agree* on the observations!

It must be emphasized that each is perfectly free to adopt the other's point of view, or to regard *both* spaceships as moving (that makes for a much more tedious calculation). The point is that relativity insists that *it makes no difference which reference frame you use* – all account equally well for the two observable facts.

What happens if one of the astronauts turns around and comes back for a direct face-to-face comparison of clocks? The answer is that it matters crucially *which* does the turning around. This is the famous *twin paradox,* of which we shall hear more later.

The 2/1 ratio between time on the *sender's* clock and the time on the *receiver's* clock applies to all subsequent transmissions. Joe's reply, sent when his clock read 20, arrived when Sue's read 40. For $v = 0.8c$ the ratio would be 3/1.

The calculations are summarized in the table on the next page. For convenience, distances are measured in light-minutes (lmin), the distance light travels in a minute, which is more than ten *million* miles! The speed of light is then 1.0, and the relative velocity of the ships is 0.6, measured in *light-minutes per minute*.

Quantity	*Sue's analysis*	*Sue's value*	*Joe's value*	*Joe's analysis*
What Sue's clock read when she transmitted	I know what I saw!	**10 min**	10 min	I accept Sue's observations *(Rule 4)*
The "true" time when Sue transmitted	I trust my own clock *(Rule 1)*	10 min	12.5 min	Moving clock, runs slow by $\gamma = 1.25$
How far apart the ships then were	*time × velocity* $= 10 \times 0.6$	6 lmin	7.5 lmin	*time × velocity* $= 12.5 \times 0.6$
Relative velocity of the message and Joe	He's moving, so $c - .6c$ *(Rule 2)*	.4c	c	I'm standing still *(Rule 1)*
Time the message spent in transit	*distance ÷ velocity* $= 6 \div 0.4$	15 min	7.5 min	*distance ÷ velocity* $= 7.5 \div 1.0$
Total time since the ships met	add the times: $(15 + 10)$ min	25 min	20 min	add the times: $(12.5 + 7.5)$ min
What Joe's clock read when he received	Moving clock, runs slow by $\gamma = 1.25$	20 min	**20 min**	I know what I saw!

Note that of all the numbers in this table, *only two* – the ones in boldface – represent actual observations. The rest are part of the superstructure we erect to obtain a working picture of reality, one in which everything we experience is understandable.

NOTES ON ASTRONOMY AND COSMOLOGY

A *light year* is nearly 10 trillion kilometers, 70,000 times the distance to our sun. Our nearest stellar neighbor, *Proxima Centauri*, is 4.3 light years away. We are part of the *Galaxy* or Milky Way, a relatively flat spiral 100,000 light years across that contains about 100 billion stars. Our galaxy is a member of a *local group* of 21 galaxies, which extend to about 3 million light years. Clusters form superclusters on a scale of hundreds of millions of light years. The solar system is 4.6 billion years old, perhaps a third the age of the universe.

A star shines for millions or billions of years, depending on its mass, which can range from about fifty times smaller to a hundred times larger than that of our sun. The heavier the star, the faster it burns, which more than makes up for the extra mass. For example, a star 10 times heavier than the sun will be more than 1000 times as luminous, exhausting its fuel 100 times sooner. The "burning" consists of turning hydrogen and helium into heavier elements. We will have more to say about this later, when we get to nuclear physics.

When a star runs out of usable fuel, it collapses into one of three kinds of *compact object*. If it is lighter than 1.3 solar masses, it gently shrinks into an object called a *white dwarf*, about the size of the Earth and terribly dense. Atoms are squeezed into a fraction of their normal space. It continues to shine for a few billion years as it shrinks further, converting gravitational energy to heat and light. A star somewhat heavier than this limit will first drive away much of its mass through a powerful "stellar wind."

When a star of more than about seven solar masses exhausts its fuel supply, its dense inner core will collapse suddenly, leading to a "rebound" explosion called a *supernova* that drives off the outer portions of the star. What remains at the core is far denser than a white dwarf. If the mass is around 1.5 solar masses, it will become a giant atomic nucleus called a *neutron star*, a few kilometers in diameter. A piece of neutron star material the size of a spitball would weigh a million tons!

Neutron stars are called *pulsars* because they spin rapidly, sending out beacons of electromagnetic energy (anything from radio to gamma rays) that sweep the Earth at regular intervals. Jocelyn Bell, who discovered the first one in 1967, while working on her PhD thesis at Cambridge, at first hoped this might be a sign of intelligent life, and she fondly called them *LGMs* (for Little Green Men).

The fastest yet found, PSR1937+21, is a terribly precise clock that rotates 600 times a second. Watching it daily with a radio telescope has confirmed that our atomic clocks change their speed as the Earth-sun distance changes, providing yet another test of general relativity.

Evidence for Black Holes

There is some uncertainty as to just how heavy a neutron star can get, but somewhere below 2 solar masses the collapse must continue all the way to a *black hole*.

When a black hole is part of a two-star (binary) system, it can reveal its presence in several ways. First of all, its powerful gravity sucks in material from the "stellar wind" emitted by all normal stars, accelerating it to nearly the speed of light. This produces x-rays. A second clue is that if its stellar partner is visible, it is possible to estimate the mass of the unseen object by studying the partner's orbital motion.

A neutron star can also emit x-rays, so both clues are needed. We now know of five x-ray binaries where no pulsar has been observed and the mass of the unseen companion is between

3 and 10 solar masses. It seems likely that these are black holes.

If a black hole is rotating rapidly, some of the matter falling in toward it will escape capture, to be ejected in narrow jets at each pole. These move at an appreciable fraction of the speed of light. It is hard to imagine any other process that can accelerate bulk quantities of matter to such speeds. Several such objects have been seen. One of these, SS433, is also the 10 solar mass binary mentioned above. Its jets move at .24c, indicated by shifts in the frequencies of light they emit.

Some galaxies have a dense core that radiates stupendous amounts of energy, equivalent to many solar masses per second. A giant black hole that gobbles stars wholesale seems the likely culprit. Our own galactic core is obscured by dust, but recent infrared observations suggest that it is fairly active, and may contain one or several black holes.

The Beginning and the End

The cosmic microwave background radiation, which dates from the time when the universe was about 300,000 years old and had cooled enough for atoms to capture electrons, can be a very revealing handle on the Big Bang. In April, 1992 scientists studying this radiation with the aid of a sattelite, the Cosmic Background Explorer (COBE), found that this radiation was not uniform in all directions, but showed irregularities of a few parts per million. These irregularities presumably originate in a non-uniform distribution of matter, and are in fact an essential part of the Big Bang theory.

In order to form stars and galaxies, matter must clump together. But if the early universe had been completely uniform, gravity would have pulled equally in all directions. Some irregularities were needed to serve as "seeds" for the clumping process. Star and galaxy formation also requires enough mass to be present, to produce sufficiently strong gravitational forces. The irregularities revealed by COBE are too small to do the trick unless there is 20 to 30 times more mass than we can see today — possibly *enough mass to eventually reverse the expansion of the universe!*

Studies of the motions of stars in galaxies show that the gravity of visible matter can not account for their orbital speeds. If most of the mass of a galaxy is concentrated near its center, the stars in the outer reaches of galaxies should move many times slower than those near the center, but instead the dropoff in speed is considerably more gradual. This can be accounted for by assuming each galaxy has a "halo" of invisible mass surrounding it, counterbalancing the concentrated mass at the center, and containing many times the mass of the galaxy. If galaxies tend to have black holes at their centers, even more mass must reside in the halo. Taken together with the COBE results, this provides some support for those who hope that the universe will not, in fact, blow away into nothingness.

Nobody has a clue as to what this so-called "dark matter" really consists of, but speculative theories abound. Many astronomers think it is something quite prosaic, cool gas or dust, while others believe it consists of exotic subatomic particles. The COBE results favor the latter interpretation, though this is hardly conclusive.

Going further back in time, the lightest nuclei (elements 1 through 4) were all formed when the universe was about three minutes old. Their relative abundance is another experimental haldle on the Big Bang. There is also the observation that the universe contains about 10 billion particles of light (photons) for every particle of matter. This ratio is a clue to conditions when the universe was about a *pico*second old!

OTHER FORCES AND THE "THEORY OF EVERYTHING"

In Einstein's original version of the theory, gravity alone determines the geometry of the universe. Other forces must be treated in the usual Newtonian fashion, leaving Einstein's revolution more a program than a full theory. Einstein's own thirty-five year effort to add electromagnetism to the geometry of the universe was a failure.

It is easy to see why this is so. Galileo discovered that when gravity is the only force, all objects put in the same place will move in exactly the same fashion. Other fields do not have this simple property. In an electric field, for example, a positively-charged object will move in one direction, a negative one in the opposite direction, and a neutral one won't be affected at all. How can you get different geometries for different objects?

In the early 1920s, an obscure German mathematician named Theodor Kaluza proposed an ingenious solution to this problem. He suggested that positive, negative, and neutral objects *can't ever really be in the same place,* because what we call electric charge is really position in an unseeable *fifth dimension*!

To use an analogy, we all know that clouds move in response to the wind. There are times when there are clouds at different heights, and the winds at these heights move in different directions, so clouds can also move in different directions. But if we knew nothing of the dimension "height," and observed clouds only from the shadows they cast on the ground, we would be hard-pressed to explain this.

How is it that there can be a dimension that we can not percieve? Kaluza and Oskar Klein, a Swedish mathematician, suggested that in this dimension the diameter of the universe might be *subatomic* – we don't see the dimension because it's *inside us*! — indeed inside every electron. All that is needed is that this dimension be smaller than the smallest distances we can observe — the present limit is 10^{-18} meters.

Einstein at first liked this scheme, but when it was shown that it gave no predictions that differed from those of Newtonian electromagnetism, he realized there could be no crucial test, no "eclipse observation" that would show it was right, and the Newtonian calculation was certainly easier. So he went on to try to incorporate electricity into four-dimensional geometry.

Today we realize that the universe we know requires at least three additional forces: two that operate inside nuclei, and one responsible for generating rest mass in all subatomic particles that have it. To accomodate all these forces, two of which are more complicated than electromagnetism, an updated Kaluza theory needs at least *ten* dimensions. Six of these must be "compactified" space dimensions *à la* Klein, leaving the familiar three plus one of time as the only ones that can be observed.

This is the basis for the "superstring" theory now in vogue, the so-called "Theory of Everything." So designating it calls for more than a little *chutzpah*, for this theory has yet to come up with an experimentally testable prediction.

Chaos Theory: How Big an Advance?

To some, it's a novel intellectual weapon that can be applied in almost every field; but to others, it's nothing less than "Gödel's child": a window into the unknown

This is the last in a six-part series that examines how scientists in a host of fields are using chaos theory to study complex phenomena. The five previous pieces, which appeared between 6 January and 10 March, reported on chaos studies in epidemiology, population biology, physiology, quantum physics, and meteorology. This article explores whether chaos is merely an interesting idea enjoying a faddish vogue or is actually, as some of its proponents claim, a revolution in scientific thought.

In politics it's called a revolution; in business, a hostile takeover. Scientists use a gentler term—paradigm shift—but the sense of sudden, radical change remains.

Some say science is in the midst of such an upheaval now. Scientific rebels marching under the banner of chaos are out to remake [illegible] world. Their goal: to replace the orderly universe of Newton and Einstein with a less predictable cosmos. Already they have won a few skirmishes, and their ideas have a powerful appeal that is attracting more followers all the time.

Yet the outcome is still undecided, and the ultimate relevance and importance of chaos theory to the real world are still unclear. When the smoke clears, will scientific history have been made, or will this all be relegated to the footnotes?

Joseph Ford has no doubts. "We are in the beginning of a major revolution," he says. "The whole way we see nature will be changed." Ford, a physicist at Georgia Tech, has been working in the field since the late 1950s, long before it had a catchy name and a high profile. His interest was piqued, he says, by one of the long-standing questions of statistical mechanics: Where does the randomness necessary for statistical behavior come from if the universe is at heart an orderly, deterministic [illegible]?

Chaos theory may offer an answer to that question, Ford says. We now know that deterministic systems—those whose behavior is described by mathematical equations—can behave chaotically, which means they act in such a complicated way you cannot predict exactly what they will do in the future. The best you can do is make probabilistic statements about them. A system as simple as the sun, the earth, and an asteroid, for example, can become chaotic. Although all three bodies act according to Newton's laws of motion, the complex influences of the two larger bodies can make the movement of the asteroid so irregular that its future positions can only be described in terms of probabilities.

This may be an important insight, but is it revolutionary? Hardly. It is not even new. A century ago, the French mathematician Henri Poincaré studied the general three-body problem and understood that in certain cases the solutions become intractably complex.

So what is revolutionary about chaos? One answer is that over the past 15 years scientists in a wide range of fields have come to realize that the world is not nearly so orderly as they once assumed. Poincaré may have known or guessed how much of the world is chaotic, but this awareness had not seeped into the general consciousness of the scientific community until recently, and perhaps not even yet. "We tend to think science has explained everything when it has explained how the moon goes around the earth," says Jim Yorke of the University of Maryland, who coined the term "chaos" in the early 1970s. "But this idea of a clock-like universe has nothing to do with the real world."

Chaos is a mathematical concept that is rather difficult to define precisely, but it can be thought of as deterministic randomness—"deterministic" because it arises from intrinsic causes and not from some extraneous noise or interference; and "randomness" referring to irregular, unpredictable behavior. The appealing aspect of chaos is that it offers a way to understand complicated behavior as something that is purposeful and structured instead of extrinsic and accidental.

Ringleaders of the chaos revolt say that for the past 200 years Western scientists have looked at a messy, complicated world and seen only this "clock-like universe." Classical physics proved so successful, they say, that it ended up limiting the way people look at nature. Now, Yorke says, "chaos gives us a very different picture of the world in which we live."

Thomas Kuhn described the effects of such a shift in scientific perspective in his famous book, *The Structure of Scientific Revolutions*, published in 1962: "Led by a new paradigm, scientists adopt new instruments and look in new places. Even more important, during revolutions scientists see new and different things when looking with familiar instruments in places they have looked before."

The theories of relativity and quantum mechanics sparked the two major paradigm shifts in the 20th century, Kuhn wrote. Relativity vanquished the false distinction between matter and energy, while quantum theory introduced the idea of inherent uncertainty. Will chaos theory beget a third paradigm shift?

Not surprisingly, both Ford and Yorke answer in the affirmative. Other scientists are more skeptical. Paul Martin, dean of applied sciences at Harvard, says, "There have been some interesting ideas, some that were around but that many scientists

Joe Schwartz/Georgia Tech

Joseph Ford: *Chaos brings us face-to-face with Gödel's Theorem.*

University of Maryland

Jim Yorke: *Chaos shows we do not live in a clock-like universe.*

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weren't aware of, but I don't think it's revolutionizing the way we look at science." The essence of chaos—the idea that the behavior of some deterministic systems can only be described statistically—may be news to some people, he adds, but "weathermen knew it 30 years ago, and many more people have realized it in many more areas."

The contribution of chaos theory has been, Martin says, to give researchers an appreciation of just how little complexity in a system is needed to produce complicated phenomena. This in turn gives rise to the hope that researchers will be able to get detailed analyses of some physical systems that previously seemed open only to statistical solutions, he says. "That's an advance, it's not a revolution."

Revolution or not, there is no denying the allure of chaos's cause. In one field after another, researchers have answered its call to arms.

In astronomy, Jack Wisdom at the Massachusetts Institute of Technology has discovered that many bodies in the solar system follow chaotic orbits. The moon Hyperion is tumbling chaotically around Saturn. The gravity of Jupiter can push asteroids in the asteroid belt into chaotic motion, and some of them end up heading toward the earth as meteoroids. Computer calculations show the orbit of Pluto is chaotic.

In physics, Richard Brewer of IBM has placed two barium atoms in an electromagnetic trap. By varying the strength of the electromagnetic field, he can propel the atoms from stability into irregular, chaotic motion and back again.

In chemistry, a number of researchers have analyzed the Belousov-Zhabotinskii reaction, an oscillating chemical reaction, and have seen the concentration of the reaction products vary chaotically over time.

But in a sense, none of these results can be called revolutionary. In each case, the system behaves according to well-understood and accepted physical rules, and researchers have simply found cases where the solutions to the equations behave chaotically instead of with the nice, orderly behavior that had been studied up to then. It is good to know that the real world does indeed behave as the mathematical equations predict, even when those equations have chaotic solutions, but it is not too surprising.

The true revolutionaries are those researchers who are engaged in fields where the mathematical models do not work so well, or maybe do not exist at all, and who are using the ideas of chaos to explain things that standard science cannot.

Ary Goldberger, a cardiologist at Harvard Medical School, is one such rebel. Goldberger studies variations in the rhythm of the heart. He hypothesizes that these fluctuations hold a great deal of information about the health of the heart. Strangely enough, a healthy heart has chaotic fluctuations in its pattern of beating, he says, while sick hearts often are much more regular in their rhythms.

The idea inherent in this approach, Goldberger says, is that a researcher can get a great deal of information by studying the variability of a system in addition to its stable order. For example, he says, [illegible] patients can have the same heartbeat statistically but with different dynamics, and their states of health can be quite different. The only way a physician could distinguish between the two patients would be by looking at fluctuations in the heartbeat that are

Art Imitates Chaos

Science usually doesn't have much to say to art. Let's face it, string theory, plate tectonics, and DNA are not likely to send painters scurrying to their canvases. But fractals and strange attractors . . . ahh, that's different.

"There's something inherently appealing about chaos, something fatalistic that everyone can empathize with," says Kevin Maginnis, an artist and president of Kaos Inc., a not-for-profit organization that backs "eccentric or anomalous efforts in art or science." Kaos Inc. is sponsoring a Chicago art show this fall whose theme is chaos, and Maginnis says the response from artists and architects has been enthusiastic.

Chaos is appealing to artists, Maginnis says, because it offers a fresh way to view the world. "The challenge is to get art that is influenced by the idea [of chaos] but that is not just illustrative of it," he says. The way to do this is to "take the idea to an intuitive, nonrational level that no scientist can express."

Klaus Ottmann, who is in charge of the visual arts section of the show, sees the appeal somewhat differently. "The main attraction for artists," he says, "is the decorative element in chaos, particularly in fractal geometry." Ottmann, an art critic and curator of exhibitions at Wesleyan University, says that decoration has been downplayed by modernist schools which have emphasized function, but chaos and fractal geometry give artists a chance to have both. "Chaos theory can bring meaning or content back into ornamentation," he says.

Maginnis and Ottmann both emphasize the attractiveness of the yin/yang relationship between chaos and order. The chaos/order dichotomy provides an "open-ended way to organize things" that "allows for spontaneity but is visually very striking," Maginnis says. Some artists, Ottmann says, attempt to "juxtapose order and chaos in a visual field," leading to such combinations as computer-generated fractal images integrated with primitive patterns.

Whatever the attraction, it is not limited to Chicago. After planning his show, Maginnis discovered the New Museum of Contemporary Art in New York City was planning a similar exhibit, and they agreed to host simultaneous shows. From 13 September to 26 November, "Strange Attractors: Signs of Chaos" will run in New York City, while "Strange Attractors: The Spectacle of Chaos" is in Chicago.

Some of the artists Maginnis contacted about the show were already consciously using ideas from chaos in their work, he says, while others recognized echoes of chaos in their work after he described it to them. "People have a natural empathy for chaos," Maginnis suggests. "Everyone's experienced it in one way or another." ■ R.P.

Chaos-inspired art: *"Puni Asymptote" by Carter Hodgkin.*

usually thought of as extraneous noise to be ignored.

Traditionally, researchers in physiology have tended to look for order and to treat whatever order was available in a system as the most important detail, Goldberger says. If he is correct in believing that fluctuations—disorder—also contain important information about a system, "it's going to transform the way people look at their experiments, the way they look at their data. People will be looking for all these chaos ideas in the data."

But are such new approaches the same as a revolution? Not in the sense that quantum mechanics or relativity was a revolution, says Steven Toulmin, a philosopher of science at Northwestern University in Chicago. Where quantum mechanics opened up an entirely new level of behavior in the physical world, chaos is merely correcting a 200-year-old mistake. "People assumed for more than 200 years that a Newtonian world was predictable," he says. "Chaos shows that this was always a mistaken assumption."

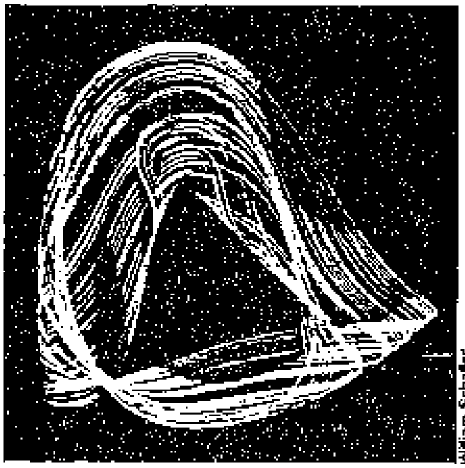
Instead of quantum mechanics or relativity theory, Toulmin thinks chaos is better compared with statistical mechanics, a mathematical tool that can be used to study various physical systems that exhibit statistical behavior. Chaos theory gives us extra intellectual weapons, but not an entirely new world view, argues Toulmin.

On the face of it, Toulmin's point seems hard to argue with. If all that chaos theory offers is the insight that there is more to the world than order and stability and that a complete description of nature must include complicated behavior, then it is not revolutionary. It suggests new lines of inquiry, offers new tools to study irregular behavior, but it is not a new world view.

However, some of the people who have studied and thought about chaos most deeply insist that there is more to come.

For instance, one deep question that has been raised but not answered is: What is quantum chaos? So far, chaos has been seen only in classical systems, and physicists do not even have a good idea of what quantum chaos should look like. But if quantum mechanics is indeed the fundamental theory of nature, it should include chaos in one form or another, since chaos is indisputably part of the natural world. The fact that no one has seen anything that can be identified as quantum chaos may reflect a shortcoming of quantum theory.

Ford, who refers to himself as the Evangelist of Chaos, says he believes chaos theory will fundamentally change our view of the world by "forcing us to face our limitations." One way it will do this, he suggests, is by bringing Gödel's Theorem to bear on physics. Mathematician Kurt Gödel proved that any mathematical system of interest is incomplete—there will always be questions that can be asked but not answered in any particular logical system. "Chaos is, in a sense, Gödel's child," Ford says. Chaos theory proves that there are physical questions that cannot be answered—where Pluto will be in its orbit 1 billion years from now, for instance.


William Schaefer

Chaos comes to life *in such computer-generated images as this strange attractor.*

Yorke's vision is broader and less specific than Ford's. To Yorke, the lessons of chaos can be nicely summed up with a line from *Hamlet*: "There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy." Or in Yorke's paraphrase: "Things are stranger than you think."

By this he means that our perception of the world is limited by our understanding of nature. Chaos, he says, promises to liberate this view from the clock-like picture of the universe that has influenced Western science's paradigm for more than two centuries. "One of the disappointments is the way the scientific community has jumped on the idea of order in chaos," says Yorke. "Now that they've found chaos, they want to look for order in chaos."

However, Yorke continues. "If we set our goals at looking for the mundane, then we will find it. The facts are that the universe is much more complicated than we imagine, and if one understands how strange the world is, one begins to look for these strange things." For Yorke and many other chaos scientists, the search is already on for these strange things. ■ Robert Pool

Everywhere You Look, Everything Is Chaotic

The chaos insurgency has opened up fronts in nearly every scientific discipline. Some of the targets are:

■ **Meteorology.** Edward Lorenz at the Massachusetts Institute of Technology got the chaos revolt rolling in 1963 with his demonstration of chaotic behavior in a much simplified model of atmospheric air flow. Meteorologists today accept that chaos in the atmosphere makes accurate predictions impossible more than a couple of weeks into the future, but some hope that chaotic models may eventually make it possible to predict long-term trends in the weather.

■ **Economics.** William Brock at the University of Wisconsin–Madison and Chera Sayers of the University of Houston have used chaos theory to look for hidden order in business cycles. They hope to improve short-range predictions of economic data.

■ **Physiology.** The brain uses chaos as a waiting state, says Walter Freeman at the University of California at Berkeley. Studies of human EEGs show that brain wave patterns become more ordered when a subject is taking in or processing information, he says. Other brain researchers are looking for ways to predict epileptic seizures by analyzing chaotic EEG patterns.

■ **International politics.** Alvin Saperstein at Wayne State University concocted a model for an arms race between two hostile nations. Experiments on a model where both countries introduced antimissile defense systems showed that the situation was chaotic and unstable, eventually leading to war.

■ **Astronomy.** Some variable stars pulsate irregularly. Oded Regev of Columbia University has done numerical modeling of this behavior and found evidence of chaos.

■ **Transportation.** The award for the most down-to-earth application of chaos theory may go to a group of traffic engineers, who, during a meeting in Washington, D.C., in 1988, associated chaos with snarled traffic patterns. Next time you're stuck in stop-and-go traffic on a rush-hour freeway, blame it on chaos. ■ R.P.

THE PAULI PRINCIPLE AND CHEMISTRY

Chemistry is concerned solely with the motions of electrons in atoms. The nucleus only serves to keep the electrons bound, via electrical attraction. The *atomic number* Z is equal to the electric charge of the nucleus in fundamental units, and hence also to the number of electrons in a normal, neutral atom.

The *Pauli Exclusion Principle* is the key to understanding atomic (also nuclear) structure. It states that electrons are "territorial." To be specific, *no more than one electron can occupy a quantum state.* Each Schrodinger wave actually stands for *two* electron states, because the electron has an internal property named (somewhat misleadingly) *spin*, which can assume two values.

In wave mechanics, each Bohr level n is replaced by n^2 wave patterns, very nearly equal in energy. Taking into account spin, this gives a series of "shells" of electrons, each with $2n^2$ members (i.e. 2, 8, 18...etc). Though the additional forces present in many-electron atoms disrupt the energy levels, all electrons in a shell tend to have roughly the same energy. The higher shells further subdivide into "subshells," with a tendency for a subshell to contain eight states.

Atoms form chemical bonds through the interactions of the outer electrons, the ones in unfilled shells or subshells. In some cases, an electron actually moves from one atom to another, leaving two charged atoms (ions) that stick together by electrical attraction. This is called an *ionic bond.* In others, electrons take on complex patterns surrounding two or more nuclei, *covalent bonds.*

Only the electrons in the outermost shell or subshell participate in chemical binding, since it takes much more energy to remove inner-shell electrons from the atom. These electrons are called *valence* electrons. Atoms with equal numbers of electrons in the outermost shell are similar in how they bond – this is the source of the regularity expressed in the *periodic table.* For example hydrogen, lithium, and sodium each have one electron in their outermost shells – the $n = 1$, 2, and 3 shells, respectively. All have similar chemical behavior, i.e. one can replace the other in most molecules. Because of the existence of subshells containing eight states, the periodic table has eight columns.

Atoms with completely filled outer shells — the so-called "noble gases" helium, neon, argon, etc. — are essentially chemically inert because it is not energetically favorable for them to either donate or accept electrons.

Atoms with four valence electrons, e.g. carbon, silicon, germanium, are the most chemically versatile, for each can form as many as four chemical bonds at the same time. Atoms with more than four form less bonds because they tend to accept electrons in forming bonds. Thus oxygen, with 6 electrons in the $n=2$ shell, forms two bonds, as in water (H_2O). But with four bonds available, carbon can serve as the backbone for complicated molecules containing many atoms, much as the "spools" in a tinkertoy set make complicated structures possible. This is the basis for life.

Protein molecules, for example, are a major constituent of living things, and some are built of more than 10,000 atoms. The pattern for building these molecules is recorded on *nucleic acids*, RNA or DNA, which can string together billions of atoms. Without four-valent atoms, no such molecules could be built.

Atoms with four valence electrons also have special electrical properties, which are exploited in semiconductor electronic technology.

NOTES ON NUCLEAR PHYSICS, ENERGY, AND WEAPONS

Nuclei consist of *protons*, which have positive electric charge, and *neutrons*, which are electrically neutral. These particles have nearly the same mass (neutrons are 0.15% heavier), and are known collectively as *nucleons*. The number of nucleons in a nucleus is called the *mass number* **A**, which is close to the mass of the nucleus in atomic mass units.

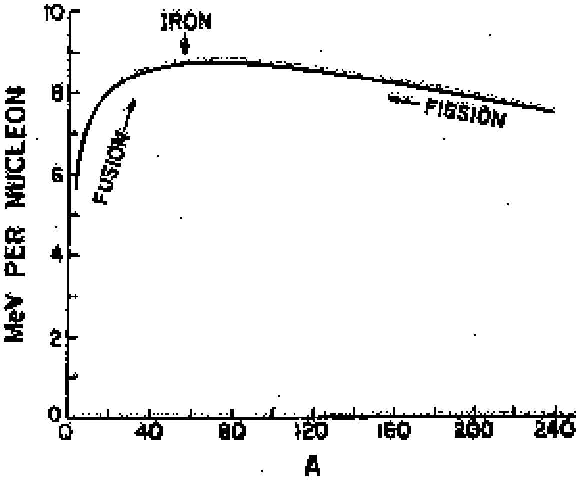
Nuclei with the same number of protons but different numbers of neutrons are the same chemically, and are called *isotopes*. Isotopes are designated by the name or chemical symbol of the element, followed by **A**. Examples – Uranium 235 or U-235 is the nucleus with 92 protons, 143 neutrons. For historical reasons, the two heavy isotopes of hydrogen have names of their own – H-2 is deuterium (D) and H-3 is tritium (T).

Nuclei are held together by a force strong enough to overcome the electrical repulsion of the protons. It is a complex force, because nucleons have small parts called *quarks*, and attractions between nucleons are the sum of many forces between their constituents.

The nuclear force dies out quickly at distances of more than 10^{-15} meters, or a *femtometer* (fm), which used to be called a *fermi*. Protons and neutrons have diameters of about 1.5 fm. This makes a nucleus similar to a liquid drop – it is held together by attractions between near neighbors, which are nearly in contact but moving rapidly. Wave mechanics demands that nucleons, like electrons in atoms, be restricted to certain allowed energy levels.

Like electrons, protons and neutrons have spin and obey the Pauli principle. Each kind of particle obeys it *separately*, so each nuclear energy level can contain two protons and two neutrons. For this reason, light nuclei tend to have roughly equal numbers of protons and neutrons. In heavier nuclei, the mutual repulsion of protons builds up and pushes their energy levels higher, so the neutrons have more low energy states available. The heaviest nuclei have about 50% more neutrons than protons.

The stability of nuclei is determined by the *binding energy per nucleon*, i.e. the average energy required to remove one nucleon. This is typically about 0.8% of a nucleon's mass, so nuclei are measurably lighter than the sum of masses of their parts. At first, binding energy grows as nuclei get larger. But as proton repulsion builds up in larger nuclei, binding energy drops off somewhat. The most stable nuclei are found around $A \approx 56$ (iron). This behavior is illustrated in the graph at the right, which is known as the "curve of binding energy."



Exploiting changes in binding energy is the basis for nuclear energy. A few tenths of a percent change in mass is typical. One can either join two light nuclei (fusion), or split a heavy one (fission). The hard part is to get a *self-sustaining* reaction; nuclei are normally protected by their mutual repulsion. *Tunneling* allows them to react nonetheless.

Elements up to iron are the product of fusion in stars. High temperatures are necessary to allow the nuclei to get close enough together so that the probability of tunneling becomes high enough to produce enough reactions to keep the process going. Since heavier nuclei repel one another more strongly, they require higher temperatures. Hydrogen burns to helium at 10 to 40 million degrees, helium at 100 to 200 million, and the last step to iron requires 3 billion. It takes the powerful gravity of a star to confine a gas at these temperatures. Light stars like our sun first burn hydrogen and later helium – iron is only made in more massive stars.

For more than 35 years, scientists have been working to confine fusion reactions on Earth, using magnetic fields as a substitute for the strong gravity of a star. The best current devices for this purpose are variants of the *Tokamak* designed in the 1950s by Andrei Sakharov. The effort worldwide has cost billions of dollars, and is still at least decades away from a practical reactor.

Energy must be *added* to build elements beyond iron. The only possible source is the gravitational collapse that leads to a supernova. Heavy elements are created in the envelope of debris blown away by such explosions, in the first second or so of the rebound, as radiation from the collapsing core of the star strikes material falling inwards and blows it away. Elements beyond helium represent less that a percent of the matter in our universe, while those beyond iron are rarer still. Since our solar system is fairly rich in elements beyond iron, it must contain supernova debris, and we are made of "recycled" dead stars.

Radioactivity is the spontaneous release of nuclear energy. It comes in three forms, which arise from completely unrelated processes:

α (alpha) – a He-4 nucleus is ejected from a larger nucleus.

β (beta) – a neutron emits an electron and turns into a proton, or a proton emits a positron and turns into a neutron. A neutral particle called a *neutrino* is also emitted.

γ (gamma) – an excited nucleus drops to a lower state by emitting a photon (with millions of times more energy than visible light photons).

α radioactivity may be regarded as a particular case of fission. β occurs when a nucleus has a lower energy state available if it converts a neutron to a proton, or *vice-versa*. γ is similar to the emission of light by electron transitions in atoms – an excited nucleus returns to its ground state.

Fission proceeds through tunneling. The nucleus tunnels from one allowed state (one big nucleus) to another (two smaller ones). In beteween lies a higher-energy state — a distorted large nucleus. A few nuclei fission spontaneously, but the process is very rare. Adding a little energy to a heavy nucleus reduces the δE and allows fission to happen very quickly. The easiest way to get this energy is for the nucleus to absorb a neutron, which need not tunnel in, because it is not repelled by the nuclear charge.

Since heavy nuclei have the highest proportion of neutrons, *fission* produces neutron-rich middle-weight nuclei that must β-decay several times to convert some of the excess neutrons into protons in order to reach stability. β-decay often leaves the new nucleus in an excited state, and a γ-decay follows. Thus fission residues are ferociously radioactive. Fissionable uranium (U-235) is a mildly radioactive α emitter, and may be safely held in your hand. But one ounce of fission residues, fresh from an operating reactor or a nuclear explosion, could give a lethal dose of radiation within a matter of minutes.

Chronology of the Development of Fission Energy

1934 Leo Szilard, contemplating the recent discovery of the neutron, concludes that large-scale release of nuclear energy would be possible if a nuclear reaction could be found that met three conditions: (1) *it is initiated by neutrons;* (2) *it releases energy;* (3) *it also releases two or more neutrons.* No such reaction was then known.

1938 (Dec) Otto Hahn and Fritz Strassman in Berlin discover an isotope of Barium (element 56) is produced when Uranium is bombarded by neutrons. Their former colleague Lise Meitner and her nephew Otto Frisch, refugees from Nazi race laws, realize Uranium must have split, and predict a large energy release.

1939 (Jan) Frisch and others confirm this. By then everyone suspects some excess neutrons will be released during the fission, and a chain reaction may be possible. There is some speculation in the press about atomic bombs, but the story is quickly forgotten.

1939 (Mar) Researchers in the US and France confirm that neutrons are emitted in fission. Germany begins funding Uranium research, under Heisenberg's direction.

1939 (Apr) Bohr & Wheeler publish a theory of fission based on the tunneling effect, and predict that only U-235 (0.7% of natural uranium) can be easily fissioned. Szilard suggests US journal editors hold back the most sensitive articles on fission lest Hitler be helped, a policy soon adopted.

1939 (Aug) Szilard drafts a letter for Einstein to send to Roosevelt. The US government begins support of fission research on a modest scale a few months later.

1941 (Dec 6) The US launches a crash program to build the bomb, fearing nuclear blackmail because the Nazi project has a two-year head start.

1942 (Dec 2) The first chain reaction (in a reactor) is achieved at the University of Chicago, under the direction of Enrico Fermi.

1943 (Apr) J. Robert Oppenheimer assembles a team at Los Alamos to design the bomb. This is a very small part of the project.

1945 (Jul 16) The first plutonium bomb is tested at Jornada del Muerte, NM.

1945 (Aug 6) The first uranium bomb is dropped on Hiroshima.

1945 (Aug 8) A plutonium bomb is dropped on Nagasaki.

Fission Reactors and Nuclear Power

Although nearly all heavy nuclei can be fissioned if you hit them hard enough, only three isotopes – U-235, U-233, and Pu-239 – will fission whenever they absorb a neutron, regardless of how little energy it has. Of these, only U-235 is found in nature. Pu-239 can be produced when U-238 absorbs a neutron and converts itself by two β-decays into Pu-239. U-233 can be similarly "bred" from thorium-232, but there is no practical need for it.

In a reactor, neutrons produced in fission are slowed down by a series of collisions with light nuclei that do not readily absorb neutrons, until they are moving no faster than the normal thermal motions shared by all atoms. At these speeds, they are readily captured by U-235, while they will rarely be absorbed by a U-238 nucleus. Then a fission chain reaction can proceed in natural uranium, or in uranium that has been "enriched" to a bit more than the normal 0.7% of U-235.

The material used to slow down neutrons is called the *moderator*, and three are commonly employed: ordinary water, heavy water (D_2O), and carbon (in the form of graphite). The latter two absorb few neutrons, and thus can run with natural uranium. Ordinary water does absorb some neutrons, so fuel for these reactors must be enriched to about 3% U-235.

The advantage of using ordinary water is that the reactor core is very compact and can be immersed in water in a steel pressure vessel. This saves construction costs, and is the preferred design for most of the world's power reactors. Its main disadvantage is that if cooling water ceases to flow, the reactor core can heat up to dangerous levels in a few minutes. Another disadvantage is that when the fuel is exhausted, the reactor must be shut down and the core removed from the pressure vessel to refuel, a process that takes it out of production for several weeks every year or so.

Safety problems with reactors originate in the fact that part of the energy release comes long after the fission, in the form of radioactivity. When a reactor is shut down, it is still producing heat at up to 7% of its operating rate. On the big reactors used to generate electricity, this is a substantial amount of heat. If cooling is lost, the fuel will melt. Backup systems must be provided, and the bigger the reactor, the more complex these are.

Early reactors used pure carbon to slow down neutrons, and water only to cool. This is the preferred design for reactors designed to produce plutonium and tritium for nuclear weapons (see below), because it wastes the fewest neutrons. About half of the power reactors in the former Soviet Union (e.g. the Chernobyl plant) also employ this scheme. Its disadvantage is that it makes the reactor core rather large and expensive to build, though in principle it can be a safe design (the Soviet version clearly wasn't!).

Nuclear Weapons Design and Manufacture

A *fission bomb* has a core containing nearly pure fissionable isotopes, with nothing to slow neutrons down, so that the reaction can build very quickly, in about a microsecond. The core must be sufficiently large and dense to insure that enough neutrons to sustain the reaction hit a nucleus before they reach the surface and escape. This is called the *critical mass*, and it can be reduced by surrounding the core with something that reflects neutrons, or by compressing it with high explosives. It ranges from about 50 kilograms for a bare sphere of U-235 to less than a kilogram of highly compressed Pu-239.

Building fission bombs requires an industry that can deliver kilogram quantities of fissionable isotopes. Not knowing what would be the best way to accomplish this, the Manhattan Project actually developed *two*.

Plutonium was made at Hanford, Washington in natural-uranium reactors. A fraction of the neutrons from fission of U-235 was captured by U-238, and the resulting Pu-239 was extracted from the fuel rods chemically. Spent fuel is so radioactive that the plant had to be run entirely by remote control. Tons of uranium were processed to get one critical mass of Pu-239. U-235 was separated from U-238 by physical processes (gaseous diffusion, electromagnetic forces) in huge plants at Oak Ridge, Tennessee.

These plants cost more than a billion 1940s dollars (about 10 billion of today's) to build, and directly employed 65,000 workers. A comparable number of people worked for contractors to the Manhattan Project. In contrast, the actual weapons design employed a few hundred scientists and engineers, with a support staff of a few thousand, at Los Alamos.

Electromagnetic separation relies on the fact that in a beam of Uranium atoms, the lighter

U-235 atoms are more easily deflected by magnetic fields. Since atomic beams carrying substantial amounts of material are hard to create and control, this is the most expensive way to make fissionable materials and was long ago discarded by the nuclear powers. But it is the route Iraq chose, because it used a minimum of imported technology and could thus be concealed.

Today, new methods are available that would make the effort much cheaper and smaller in scale, especially for a nation willing to build up a small nuclear stockpile gradually. Most of what was learned at Los Alamos is now available in the public prints, and any reactor is a potential source of plutonium. A small team of scientists and engineers of ordinary skill could design and build a workable bomb.

Given the materials, the bomb design is relatively straightforward. The problem is to *assemble a critical mass quickly*, before the reaction has time to build up and blow it apart.

The easiest way is to make a sphere of U-235 with a hole through it. The sphere is attached to the barrel of a gun, which fires a slug of U-235 to fill the hole. This was the Hiroshima bomb, and was so simple the designers saw no need to test it before it was used. They also had too little U-235 to build two bombs within a reasonable time.

A more efficient method is to surround a sphere of fissionable material with high explosive, which is detonated at the outside, producing an *implosion* that compresses the material until it becomes critical. This was the design of the bomb tested in New Mexico, and the one dropped on Nagasaki. It is the only method that works for plutonium.

The problem with plutonium from a reactor is that it can never be pure Pu-239, but contains an admixture of Pu-240. This isotope can fission spontaneously, leaving a background level of neutrons always present in the plutonium. These neutrons can start the chain reaction prematurely, before the core reaches full criticality, so the core would blow itself apart without releasing much energy. Implosion reaches criticality more rapidly than a gun design would allow.

Most fission bombs in the US stockpile are multi-layered implosion bombs containing both U-235 and Pu-239. The hard part of the design is to detonate a sphere of high explosive everywhere on its surface at the same time. This takes a device called an *explosive lens*, which is subtle to design and tricky to build, but the principles are now widely known and they are even commercially available.

A *fusion bomb*, or H-bomb, is subtler still. The high temperatures needed to start fusion in a mix of light nuclei are generated by a fission bomb trigger. You can't just pack the fusible material around the fission bomb – it would blow apart before the reaction started.

The trick is to take advantage of the fact that in the first instants of a fission explosion, much of its energy is in the form of short wavelength light (ultraviolet and x-rays) moving much faster than the neutrons or fission fragments. These heat a blanket of plastic foam wrapped around a cylindrical fusion core, which is heated and compressed until fusion is kindled.

Most fusion cores consist primarily of *lithium deuteride*, a white powdery compound of the isotopes Li-6 and H-2. The reaction starts when Li-6 absorbs a neutron and splits into He-4 and H-3. The H-3 then combines with H-2 to form He-4 and a neutron, which can in turn start the chain over again in Li-6. This sequence of reactions gives about three times more energy per unit weight of fuel than fission.

Some bombs rely on fission neutrons from a second fission core within the fusion core to get the sequence started, while others contain some tritium to start the chain. This is the most efficient design, but tritium is expensive and unstable – it is radioactive with a half-life of 12 years. So some of our most efficient bombs "spoil" and become inoperative after a few years. Tritium is made in the same reactors that breed plutonium, by inserting lithium in the reactor. There are no such reactors now in operation.

Nuclear Stockpiles and Proliferation

Prior to the breakup of the Soviet Union, the two superpowers had deployed arsenals of about 12,000 strategic warheads each, plus several thousand "tactical" (battlefield) weapons of modest power. The START I treaty calls for the removal of about one third of the strategic arsenals, and START II calls for a reduction to 4000 each, which still represents a subtantial "overkill." Both sides have taken strategic weapons off alert status and decommissioned all tactical weapons.

Because of the sheer technical difficulty, dismantling operations may take decades to complete. To complicate matters, the former USSR's weapons are now dispersed among four nations – Russia, Ukraine, Kazakhstan, and Belarus. The latter three have pledged to abandon all nuclear weapons, but have taken few practical steps to implement this.

Britain, France, and China have 300 to 500 weapons each. Israel does not admit having a nuclear stockpile, but there is evidence that it has somewhere in the range 100-200 fission weapons. India has fired test explosions but is not believed to have a stockpile. Pakistan has an active program that may soon give it a modest nuclear capability. South Africa admits to having built six fission weapons in the early 1980s but claims these have since been dismantled. Argentina and Brazil have both worked on nuclear weapons, but the current governments in these nations have signed an agreement to terminate this work and dismantle all nuclear weapons research facilities. North Korea has some sort of program, but little is known publicly about how far along it may be.

Even a small, semi-industrialized nation could become a nuclear power within a few years for an investment of a few billion dollars. The monitoring system currently in place through the International Atomic Energy Agency (IAEA) may be incapable of detecting such a program in the face of determined efforts to conceal it.

The Military-Industrial Complex and "Competitiveness"

In the US and Russia, the creation of huge nuclear arsenals spawned an immense complex of weapons laboratories, manufacturing plants, and military forces that employ hundreds of thousands of people whose careers are tied to nuclear weapons. Any bureaucratic structure this large has a great deal of political muscle, and a natural tendency to fight for its life. Thus it will take a great deal of political will on both sides to rid us of the Sword of Damocles that continues to hang over our heads.

The nuclear establishment is just a small part of a much larger entity called the "Military-Industrial Complex," a term that originated in President Eisenhower's final state-of-the-union address in 1961. Though the Complex produces only about 6% of the gross national product in the US (substantially more in Russia), it employs nearly half of all the trained scientists and engineers in each country.

Though military R&D does occasionally produce "spinoffs" of benefit to the civilian economy, as the technical arms race has progressed military and civilian technologies have tended to diverge. For example, the jet age in commercial aviation was launched in 1958 with the

Boeing 707, a civilian version of the Air Force's KC-135 air tanker, which had in turn been developed on experience gained with the B-52 bomber. By the late 1960s, when wide-body jets appeared, there were distinct military and civilian projects with little technology transfer. Today the cutting edge of military aircraft design is the B-2, and it is hard to imagine an airline paying several billion dollars for a plane invisible to radar! Only the instruments in the cockpits of today's jet transports owe much to their military counterparts.

This is perfectly natural, for in a technological arms race a small advantage in performance justifies a large increase in price, and most of the R&D is paid for by the customer in advance of production. A similar situation exists in auto racing, which has had hardly any connection to passenger car design for decades.

Thus a growing number of experts now believe that military R&D has probably been a drag on the US economy. Conversely, they assume, it represents a talent pool that can be tapped to make us more competitive in the international economic arena. This is not, however, an asset that is easy to convert to civilian use.

Technologists whose careers have developed in the Complex have a hard time adjusting to the civilian economy, in which R&D must be paid for out of sales, and a significant gain in performance is required to justify any real price increase. This was demonstrated in the 1970s, when in the face of diminished military budgets a number of weapons firms tried to develop products that would address the "energy crisis." In most cases they came up with exotic solutions that were simply not economical. Thus it will take a major shift in attitudes before these organizations and individuals will be of use to the civilian economy.

Even if this readjustment does take place, it will run up against problems with US corporate management, which has a bad track record at turning new technology in the laboratory into better products coming out of the factory. Top corporate executives tend to have backgrounds in the "fast tracks" of finance and marketing, where new efforts can bear fruit on a time scale of months and lead to a rapid rise up the corporate ladder. Production management has a lower status, and too often assumes that workers are both stupid and lazy, a self-confirming hypothesis. This spills over into our educational system, which is structured on the assumption that there will always be plenty of jobs for people with limited education. Finally, even enlightened management is plagued by "impatient capital," investors who demand immediate profits at the expense of long-term goals.

In the current wave of corporate "downsizing," research has often been among the first areas to suffer. In many firms, what research remains is hardly managed at all. It often takes place far from the plant or corporate headquarters in a "think tank" modeled after a university research laboratory, which does a great job at fundamental research but is ill-suited to the needs of industry. The laboratory often has little contact with the rest of the corporation. A new product is dumped in the lap of the production staff with no realistic thought as to how it will fit into the flow of work.

Many leaders in government and industry harbor an image of technological progress as a matter of dramatic "breakthroughs," spawning new products that could scarcely have been previously imagined, and which quickly build up billion-dollar markets. The example most often cited is the semiconductor industry. But a close examination of the history of that very industry reveals a quite different scenario of development.

Semiconductor chips are, in effect, "printed" on wafers of silicon by a variety of techniques closely related to the ordinary photolithography that was used to print the pages you are now reading. Thus this industry shares the economics of scale of the printing business. After an elaborate and expensive preparation of material to be reproduced, and setup of the machines that will do the job, thousands or millions of copies can be made very cheaply. Furthermore, additional complication in the images reproduced adds little to the cost of production. It does, however, add a great deal to the one-time development costs: while the first "microprocessor" (computer-on-a-chip) was launched by a then-small firm (Intel) with a modest budget, Intel's latest chip has cost more than a billion dollars to develop! This generates pressure to seek the widest possible range of applications so as to create a mass market.

Over its 30-year history, this industry has increased the number of components on a chip from roughly a dozen in the first commercial units to more than four million today. This has taken place incrementally, with the number of components on a chip doubling roughly every 20 months.

The driving engine behind this progress has been the gradual improvement of production techniques and quality control, a process in which experience on the shop floor has played as great a role as research in the laboratory. In many succesful firms, engineers follow their products through to realization in the factory, and give serious attention to the suggestions of production workers. Though the initial successes of this scenario were achieved in small firms in the US, the lesson they taught was more widely appreciated in Japan, where consumer products are developed by the same strategy of incremental improvement, with production and research working hand-in-hand.

The largest US firms find it hard to integrate this kind of strategy with their hierarchical corporate cultures. Many are far more comfortable with military R&D contracts, which need not lead to a cost-effective product. But such is the efficacy of the other approach that today few of the advanced weapons in the US arsenal can be built without Japanese semiconductor chips originally developed for consumer products.

It has been suggested that the Cold War ended because the US persevered in weapons development, forcing the USSR into bankruptcy in the effort to keep up. This is a debatable point, and in any event it is clear that we ended up not too far from the brink ourselves. The "New World Order" will be dominated not by the strongest military power, but by those nations that best put advanced technology to the service of human needs and the protection of the environment.

Success in these endeavors will rest on fully developing and utilizing the talents of all citizens, both through formal education and on the job. We must learn to accept education not as something that terminates with a diploma, but as a lifelong experience. In the final instance, human resources are the most valuable assets a nation can have.