Physics for Future Presidents
a textbook

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Chapter 1. Energy, Power, and Explosions

(updated 2/26/02 with corrected calculation for weight of TNT)

Introductory story

> At the end of the Cretaceous period, the golden age of dinosaurs, an asteroid or comet about 10 miles in diameter headed directly towards the Earth with a velocity of about 30 miles per *second*, over ten times faster than our speediest bullets. Many such large objects may have come close to the Earth, but this was the one that finally hit. It hardly noticed the air as it plunged through the atmosphere in a fraction of a second, momentarily leaving a trail of vacuum behind it. It hit the Earth with such force that it and the rock near it were suddenly heated to a temperature of over a million degrees Centigrade, several hundred times hotter than the surface of the sun. Asteroid, rock, and water (if it hit in the ocean) were instantly vaporized. The energy released in the explosion was greater than that of a hundred million megatons of TNT, 100 *teratons*, more than ten thousand times greater than the total U.S. and Soviet nuclear arsenals.. . . Before a minute had passed, the expanding crater was 60 miles across and 20 miles deep. It would soon grow even larger. Hot vaporized material from the impact had already blasted its way out through most of the atmosphere to an altitude of 15 miles. Material that a moment earlier had been glowing plasma was beginning to cool and condense into dust and rock that would be spread world wide.. . .
>
> -- adapted from Nemesis (1987)

Few people are surprised by the fact that an asteroid, the size of Mt. Everest, could do a lot of damage when it hits the Earth. And it is not really surprising that such bodies are out there; every few years, there is a newspaper headline about a "near miss" in which an object misses the Earth by "only a few million miles." But why should an asteroid impact cause an explosion? It was made of rock, not dynamite. And why such a big explosion? But then, what is an explosion, after all?

An explosion occurs when a great deal of energy is "released" into a small volume in a very short period of time. It doesn't matter what the source of the energy is; it could be chemical (stored in food), or kinetic (the result of motion).

Before we get too abstract, let's consider an example that amazes most people when they first see it. In the table below, we'll give the amount of energy present in different objects. We'll take the mass of each object to be the same: 1 gram. (There are three grams in a penny, five in a nickel, one in a cubic centimeter of water, 28 in one ounce, 454 in one pound, and 1000 in one kilogram.) We'll measure energy in "Calories", also known as food calories.

object	**Calories in one gram**
gasoline	10
chocolate chip cookies	5
bullet (moving at speed of sound)	0.01
methane gas (CH_4)	13
battery (flashlight)	0.01
battery (computer)	0.1
hydrogen gas (H_2) for fuel cell	26
TNT or dynamite, by convention*	1 (see footnote *)
real TNT (trinitrotoluene)	0.651
modern High Explosive (PETN)	1.06
meteor (at 30 km/sec)	100

*For weapons limitations treaties, 1 gram of TNT is defined as have 1 Cal. Thus, for example, an explosion that releases an energy equivalent of one ton of TNT will be a million Calories, i.e. a megaCalorie.

Study that list. There are some real surprises in it. Chocolate chip cookies contain fives times as much energy as the same weight of TNT! That is the example that surprises the most people. How can that be true?

The answer is that TNT is not used because of its enormous energy. It is used because it can release that energy very quickly. Power is the rate of energy release. TNT has greater power than chocolate chip cookies. Power = Energy/time. Energy = Power x time.

interesting fact: Not all brands of explosive release exactly the same amount of energy. So for purposes of international treaties, one gram of TNT is *defined* as having exactly 1 Calorie of energy. This is important, for example, when placing limits on permitted nuclear explosion tests. A nuclear bomb is described in terms of its TNT equivalent. The Hiroshima bomb, for example, was measured to have released the equivalent of 13 kilotons of TNT. A modern nuclear bomb can release the energy of a megaton of TNT. One ton is approximately one million grams. So a megaton of TNT releases a million million Calories of energy. In scientific notation, that is 1E12 Calories = 10^12 Calories.

another interesting (but less important) fact: When President Truman announced that an atomic bomb had been dropped on the Japanese city of Hiroshima, he mistakenly announced that the yield was 20 kilotons of TNT. He was using the number for the nuclear test that was made in New Mexico, and he didn't know that the Hiroshima blast had been measured to be "only" 13 kilotons TNT equivalent.

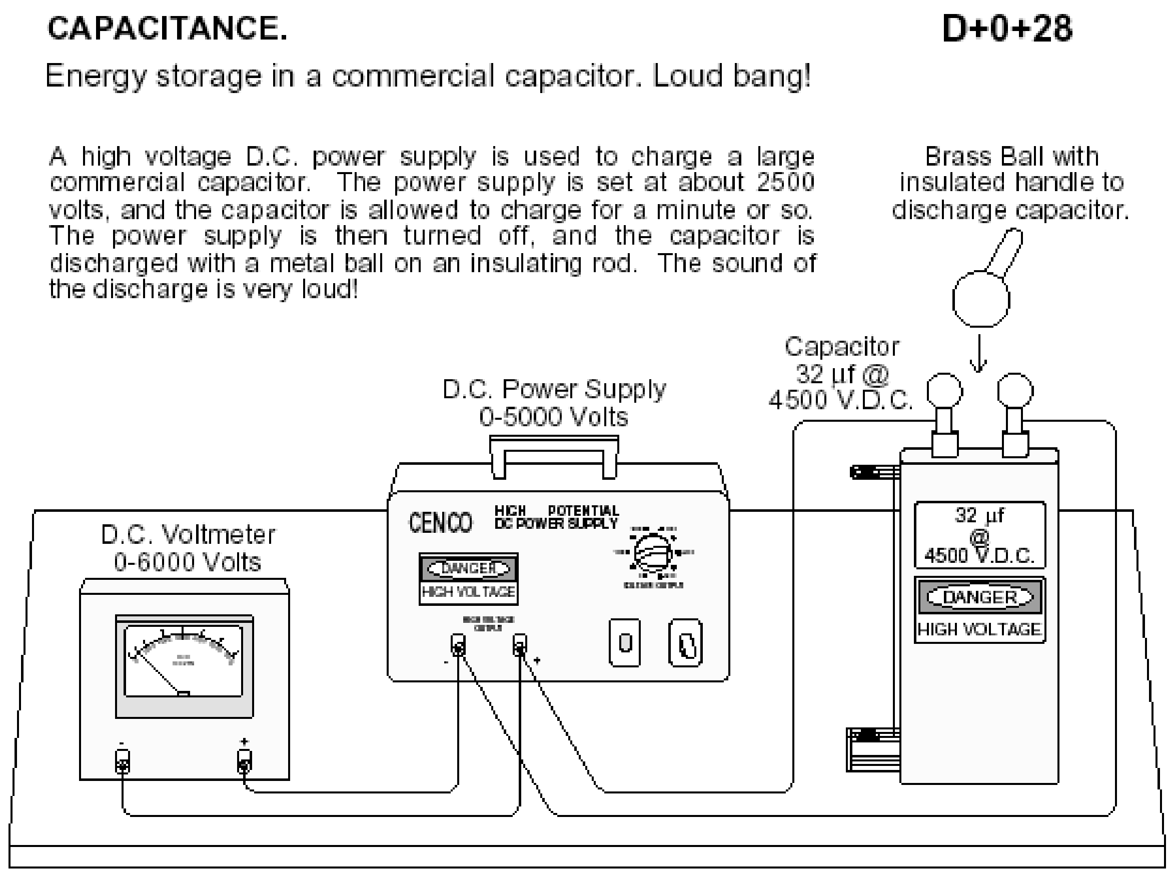
fuel-air explosives. (This section was added on Nov. 6, after the US started dropping 15,000 lb fuel-air explosives on Taliban troops. What is a fuel-air explosive? You can probably guess. It consists mostly of gasoline. The gasoline is dropped, usually on a parachute. As it near the ground, a small charge of high explosive (probably only a few pounds worth) explodes in the center, dispersing the gasoline over a large area of air. The gasoline mixes with the air, and is then ignited. The explosion is spread out over a large area, so it doesn't exert the same kind of intense force that it takes to break though a concrete wall. But it has enough energy released to kill people and other "soft" targets. What makes it so devastating is the fact that 15,000 lbs of gasoline contain the energy equivalent of 150,000 lbs of TNT. So although 15,000 lbs sounds bad enough, in fact it is much worse than it sounds.

Gasoline must be mixed with air to release energy; in an automobile, this is done in the carburetor or the fuel injector. A mixture of fuel and air is exploded in the cylinder of a car, and it literally explodes. Because the cylinder is small (less than a liter in volume), the explosion is small. But the energy released from that explosion pushes a piston, and that is what drives the wheels of the car. An "internal combustion engine" is really an "internal explosion engine."

If a lot of gasoline is suddenly mixed with air (e.g. in a crash, or in a "Molotov Cocktail" used by a rebel), then it also explodes. In the Persian Gulf War of the 1980s, there were stories about "fuel air explosives" being used. These are large containers of gasoline that are first blown apart, so they mix with air, and then ignited, so the mixture explodes. As the table shows, such explosions are potentially ten times as energetic as the explosion of a TNT bomb of the same weight.

If you want to destroy a car, you can do it with TNT. But more energy could be obtained by feeding an equal weight of chocolate chip cookies to a group of people and giving them sledgehammers. But some tasks, such as cracking rocks, require great force rather than great energy. For those tasks, TNT is often better and more convenient. You can feed people chocolate chip cookies, but you also have to pay them. TNT is cheap.

Demonstration: to illustrate the difference between energy and power, I slowly charged a large capacitor in class, and then suddenly released that energy, turning it into heat and sound. Here is a description of the demonstration:



Digression: Energy crisis or Power crisis? In 2001, there were electric blackouts in California because of an "energy shortage." Yet California did not run out of gasoline or natural gas, and that is what it uses to produce energy. In fact, there was no energy shortage; there was a power shortage. To convert gasoline to electricity requires a large factory (a "power plant") that burns gas and uses it to drive an electric generator. There were not enough power plants to convert all the available gas into power, so there was a shortage of power.

Continued digression: trading energy for power. Early in the California crisis, the energy commissioners of California recognized that we had plenty of fuel to make power, but not enough power plants. In the Pacific northwest, such as the state of Washington, the problem was just the opposite. They had plently of power plants, but their energy came largely from water flowing through dams; it was hydroelectric. The snowfall had been light, and the dams weren't full, and once the water ran out, Washington would have no more energy. Washington had an energy shortage; California had a power shortage. So an agreement was reached. Washington would send extra electric power to California on hot days, helping California avert a blackout. California would pay Washington back by supplying electric energy in the evening when there was no shortage of power. California gave Washington twice as much energy as Washington gave California, and California averted some blackouts. Washington saved water (because it got twice the energy back from California). Both sides won.

Look at the table again. Are there other surprises? Look at the amount of energy stored in a battery, compared to that in gasoline. For the same weight, an ordinary (flashlight) battery has 0.01 Cal per gram, versus 10 for gasoline. Gasoline contains 1000 times as much energy. So you should not be surprised that we are not yet driving electric cars. Very expensive batteries (such as those used in computers) contain ten times as much energy per weight as do inexpensive batteries. But they are still 100 times worse than gasoline.

Digression: Electric cars. Battery powered cars have not been very successful, largely because the energy stored in a battery is about a thousand times less than the energy stored in an equal weight of gasoline. An electric car must be frequently recharged, after a hundred miles or less. (Some electric cars go further, but only because they use all the space in the car for very expensive batteries.) But electric cars have a unique advantage: when a car is going *down* a hill, the electric motor can easily be turned into a generator, and the energy that the car picks up from gravity can be used to recharge the battery. In an ordinary car, the speed while going downhill is controlled by brakes, which just turn the energy into heat. Even more important for urban "stop and go" driving, is the energy lost by using brakes to turn kinetic energy into heat. Electric cars can slow down by going into the generator mode: using the motion of the car to charge up the battery, thereby slowing the car. Despite this advantage, it is the author's considered guess that pure battery-driven cars will remain a small speciality item within our lifetimes. For that to be wrong would require a great advance in battery technology. That is possible, but probably will not occur in the next few decades.

Continued digression: Fuel cells. Fuel cells are similar to batteries, but instead of being charged by a generator, they get their electricity by using fuel. The fuel that most people are excited about is hydrogen gas, for several reasons. Hydrogen gas contains an energy per gram greater than that of gasoline. Moreover, when it reacts with oxygen in the fuel cell to produce electricity, the only "waste" produce is water vapor. We believe that this can be released harmlessly to the atmosphere. The main disadvantage of fuel cells is that hydrogen is not very dense. Even if liquefied, it has a density of only 0.071 grams per cubic centimeter, a factor of 10 less than gasoline. Per gram, hydrogen is twice as good as gasoline. Put these together, and we find that one gallon of liquid hydrogen stores five times less energy than one gallon of gasoline. Most experts say the factor is closer to three times worse (hydrogen can be burned more efficiently). Nevertheless, I am not willing to make a prediction; it is possible we will be driving hydrogen-driven cars in the near future. Where does the hydrogen come from? There is not much free hydrogen gas (or liquid) in the environment; it must be manufactured, and that takes energy (which would presumably come from solar, fossil fuel, or nuclear plants).

Still further digression: Hybrid cars - - a surprising invention. One of the more ingenious ideas in recent decades is a car that combines a battery with a gasoline engine. The car runs from the battery, and the gasoline engine runs a generator that charges the battery. This sounds ridiculous! Why not just use the gasoline engine alone? The answer lies in the details. It turns out that gasoline engines can be made to operate more efficiently if they don't have to change speed, if they always operate at the optimum conditions.

So in the hybrid, the gasoline just charges the battery. Moreover, when slowing down (or going down hill), the power from the wheels can be fed back into the battery, just as with a pure battery engine. So the hybrid gives a much better fuel economy, i.e. instead of using a gallon of gas to go 20 to 30 miles, it can use less; we can travel 60 to 100 miles on one gallon. The battery can be much smaller, because it doesn't have to hold a charge for hundreds of miles. I think it likely that hybrid cars will replace gasoline cars as the most common vehicle in the US in the near future.

Digression: a fantasy. I have an interesting idea for an invention, and I'd like you to consider it. I think I can make a carriage that would not require horses, but could take people on roads where ever they wish to go at 70 miles per hour. It would require fuel, but the fuel would be so good that it would contain ten times as much energy as an equal amount of TNT! So with just 10 gallons, you could go 300 miles! The fuel is called gasoline. The fuel will reduce pollution, since the streets will no longer be filled with horse manure. (Our children get tetanus, not from "rusty nails", but from nails covered with horse muck.)

Oh - you say - with that much energy, isn't the fuel explosive? No it isn't! It's safe! Sort of. Of course, it is not explosive only as long as we don't mix it with air. If it is mixed with air, then it will explode; in fact, you could make a fuel-air bomb. . . But it won't get mixed with air. Unless the car crashes, of course. You see, this fuel is liquid, not solid like TNT. So if you crash, there is some danger that it will get sprayed around, and become an explosive. But we'll put it in a strong tank. The fuel is so compact that there's plenty of room for it, right behind the passenger seat. It will be at least a foot away from them.

Will the tank be strong enough to withstand a collision at 70 miles per hour? Well, not always, but there are some risks involved in all new technologies. We'll require all drivers to be licensed. And besides, our calculations show that the risk is minimal. Even if everyone in the United States drove one of these vehicles, only 40,000 of them would be killed, each year.

Other units. There are several other units of energy that are worth knowing. The "watt-hour" is approximately equal to one food Calorie. (It is actually 0.86 Cal.) A kilowatt hour (kWhr) is approximately equal to 1000 Calories (it is actually 860). The favorite energy unit of physicists is the "joule". There are 4200 joules in one Calorie. Another unit is the calorie. There are 1000 calories in the Calorie. (I won't apologize for this terminology, because I didn't make it up. The Calorie, or "food calorie", is 1000 times bigger than the physicist calorie.) A Watt (usually capitalized, since it was named after James Watt), is a unit of power. It is one joule per second.

Discussion topic. Do people consume more energy every day from food Calories, gasoline, or electricity? Think about a family living in an apartment or a house. Maybe your own. (If you live in a dorm, you are sharing so many resources that it is hard to estimate electric usage.) A typical light bulb is 100 watts, a typical refrigerator uses 100 watts. At $0.20 per kWhr, how many Calories are expended in electric energy for a house that has a monthly electric bill of $60?

Medieval units: the horsepower. I think it is delightful that we measure the power of automobile engines in terms of the number of horses they replace! We also do this for airplane engines. Horsepower now has a technical definition: 1 horsepower (abbreviated 1 hp) is equal to 746 watts.

For most purposes, just think of a horsepower as almost one kilowatt. A kilowatt is the power required for a very bright electric lightbulb.

Astonishing fact. Let's use this to uncover an astonishing fact. We buy electric power from a utility company at a cost of about 20 cents = \$0.20 per kWhr. When we buy a flashlight battery, how much do we pay for the energy? A small flashlight delivers approximately 1 watt for about 1 hour; that is, it gives about one watt hour, which is one thousandth of a kilowatt hour. It costs about a dollar. So you are paying \$1000 per kilowatt hour for battery power, and \$0.20 per kilowatt hour for electric utility power. The difference is a factor of 5000! That's why people who leave their lights on when they leave their house, will be very careful to turn off their flashlight when they are not using it. (Of course, you could use rechargeable batteries! But most people don't, because they forget to recharge them.)

Solar energy. Many environmentalists believe that the best source of energy for the future is solar. It is "renewable" in the sense that sunlight keeps coming as long as the sun shines (and it is expected to have many billions of years left). It can be converted directly to electricity by using silicon solar cells. These cells have a special crystal structure in which the arrival of sunlight causes an electron to jump from one part to another. Chlorophyll in plants also convert sunlight into useful energy, but they convert it to stored chemical energy rather than into electricity.

The power available in sunlight is about one kilowatt per square meter. A solar cell can only recover about 15% of this, or about 150 watts per square meter. Suppose you wanted to build a large power plant to supply energy to a city. A large nuclear power plant can produce about 1000 megawatts of power = 10^9 watts = 1 Gigawatt. To get this much energy from solar cells would require an area of $10^9/150 = 7 \times 10^6$ square meters. Opponents of solar energy say this is huge; it would plaster the country with solar cells. But 7×10^6 square meters is only 7 square kilometers = 2.7 square miles. That would be enough for a small city. Anybody who thinks this is large hasn't driven across Nevada.

Another criticism of solar power is that it is available only when the sun is out. Of course, that turns out to be when we need the most power, to run our factories and air conditioners. I would be very surprised if solar does not turn out to be the main source of power in the future.

Could we save the energy generated during the day for use at night? Remember, batteries didn't work well for automobiles because they took up too much space. If they are not going to move, then you can afford to use large arrays of batteries. Others have suggested that the energy can be stored by pumping water up back into reservoirs. But I don't think energy storage is a big problem as long as the main energy use continues to occur during the daylight hours.

Solar powered automobiles and airplanes. There is an annual race across Australia for "solar powered automobiles." The fundamental problem with such a vehicle can be seen from the fact that one square meter of sunlight has about 1 kilowatt of power, which is equal to about one horsepower. Since solar cells are only about 1/3 efficient, that means that you need a three square meter solar cell just to get one horsepower. Typical cars have engines that run with greater than 100 horsepower, so you can see the problem. To read more about the annual race, go to their homepage http://www.wsc.org.au/index.shtml.

Given that difficulty, it is surprising to discover that a solar powered aircraft has successfully flown! Actually, it isn't truly an airplane. It doesn't carry passengers, so it is called an aircraft, a drone, or an UAV (for "unmanned air vehicle"). The aircraft was built by the company AeroVirnonment, started by the engineer Paul McCready (who designed the airplanes that flew based on human-powered pedaling: the Gossamer Condor and the Gossamer Albatross). The aircraft is named the "Centurian". The solar cells are on the wings. They have to be big to gather enough solar power to run the engines, and to give lift, and yet light in weight. The Centurian has a wingspan of 206 feet. That is greater than for a Boeing 747! The total solar power from the solar cells is only 28 horsepower. The wings also have solar cells on their undersides, to convert light that bounces off the earth. The entire weight of the Centurian is 1100 pounds. It is designed to fly above 100,000 feet. (Usual airplanes fly at about 40,000 ft.) For more information, see the AeroVironment web page:

http://www.aerovironment.com/area-aircraft/unmanned.html.

Discussion topic: why haven't we already switched to solar? Some people think it is because of political influence of the oil companies. Others say that solar is still too expensive, and we will convert when the price comes down (or the cost of gas goes up). See what you can find (e.g. on the internet) about the cost of solar.

Human power. A human pushing on pedals (e.g. riding a bicycle) can generate energy at the rate of about 100 Watts, i.e. about 1/7 of a horsepower. A trained cyclist can do 0.4 horsepower for several minutes. It was using this power to run a super-light airplane, the "Gossamer Albatross, that a bicyclist, Bryan Allen, made the 23 mile flight across the English Channel in 1979. A man can produce 2 horsepower (1.5 kW) for short bursts.

Kinetic energy. Another astonishing fact found in the table is the fact that a meteor has 100 times as much energy as the same weight of TNT. Understanding this is one key to understanding why the impact of an asteroid caused a tremendous explosion. So let us spend a little time understanding the physics of kinetic energy, the energy of motion.

The basic equation of kinetic energy is that it is equal to some constant times the mass times the velocity squared. Written down, this becomes:

$$\mathbf{E = k\, m\, v^2}$$

Notice how similar this equation is to the famous equation of special relativity: $E = m c^2$. The similarity is not a coincidence. We'll discuss the relativity equation later in this book. But it will help you to remember the kinetic energy equation.

The value of the constant depends on the units that you use. If you measure energy in Calories, mass in grams, and velocity in kilometers per second, then the constant is equal to 1/8 = 0.12. But some people like to measure their velocities in miles per hour. In the table below we give the value of the constant for different values of the units.

units	**k**
E in Calories, m in grams, v in kilometers per second	1/8
E in joules, m in kilograms, v in meters per second	1/2
E in ergs, m in grams, v in centimeters per second	1/2

E in Calories, m in kilograms, v in miles per hour	2.4×10^{-5}

The second and third entries in the table above are the ones used in most physics books. Physicists prefer energy units of *joules* and *ergs*. There are 10 million ergs in a joule. If you want to read physics books, you have to know these units.

How fast are meteors? A meteor is a space rock that runs into the Earth. Part of its velocity is its own, and part is the velocity of the Earth, which is moving around the Sun. How fast is that? The answer is surprising.

> **Optional calculation**. If you remember the distance of the Earth to the Sun (93 million miles) then it is easy to calculate the velocity. The path of the Earth around the sun is the distance times 2 pi. The number of hours it takes to go around once is 24 x 365. (There are 24 hours in the day, and 365 days in each year.) Put these figures together to calculate the velocity. The answer is astonishing.

Astonishing fact. We are all moving at 30 km/sec = 19 miles/sec around the sun. Exercise: convert that to miles per hour.

More astonishing fact. The Sun (and the Earth with it) is moving around the Milky Way Galaxy at a speed of 300 km/sec = 190 miles/sec. Moreover, the Milky Way is moving past other galaxies at a velocity of 300 km/sec. But since the motion of the Sun around the Milky Way is in a different direction from the motion of the Milky Way, the two velocities don't add, and the net velocity of the Earth is between 300 and 400 km/sec.

Discussion topic. Why don't we notice that we are moving so fast? (This is actually a very deep question, and leads ultimately to the "Theory of Relativity." More on that in a later chapter.)

But now back to our meteor problem. When a meteor crashes into the Earth, we expect the velocity to be about 30 km/sec, maybe a little more (if it hits head on), maybe a little less (if it hits from behind). How much energy is there in a one gram meteor? We'll use the kinetic energy equation given above. The velocity is 30 km/sec. This gives:

$$E = k\, m\, v^2 = (1/8)\ (1)\ (30)^2 = 108 \text{ Calories} \approx 100 \text{ Calories}$$

So the kinetic energy in a typical one-gram meteor is 100 times greater than the energy released when one gram of TNT explodes.

> **Optional calculation.** The speed of sound is about 330 meters per second ≈ 1000 feet per second. Based on this, verify that the kinetic energy of a one-gram bullet, traveling a the speed of sound, is approximately 0.01 Calories, as stated in the table.

Interesting and important digression. In the anti-ballistic missile program that is under consideration by the military, the missile would be hit by a rocket when it is moving at a velocity of about 7 kilometers per second, i.e. v = 7,000 meters/sec. Does it make sense to fill the rocket with TNT? From the point of view of the missile, the rocket is approaching it at 7,000 meters per second. The kinetic energy of each gram of the rocket is

$$E = (1/8)(1)(7)^2 = 5.9 \text{ Cal}$$

Thus the kinetic energy of the rocket (seen from the missile) is nearly six times what it would have if it were made from TNT. It is hardly necessary to make it from explosives; the kinetic energy by itself will destroy the missile. Some people say that all you have to do is put a rock in the way of the missile, and it will be destroyed. The rock has to have the capability to be in the right place at the right time. This has given rise to the term "smart rocks."

Back to the asteroid impact

What happens when an asteroid, the size of Mt. Everest, hits the Earth? Mt. Everest is big, but it is only one thousandth the size of the Earth. (Everest is about 10 km in height; the Earth has a diameter of about 12,000 km. That's roughly a factor of 1000.) That is similar to a mosquito, with a diameter of 2 millimeters, running into a truck which has a diameter of 2 meters. The truck isn't deflected, but a mess is left on the windshield.

Likewise, a Mt. Everest hitting the Earth is not going to change the obit of the Earth very much. The key parameter is the mass. The Earth will recoil, but since its mass is a billion times larger, it will recoil only a billion times less. So even if the asteroid is moving at 30 km/sec, the recoil of the Earth will be a billion times less.

Earth recoil. What do we get if we take a velocity of 30 km/sec = 30,000 meters/sec, and divide by a billion? We get $3\text{x}10^4 \text{ x } 10^{-9} = 3\text{x}10^{-5}$ meters per second = 30 microns per second = 1/1000 inch per second. That is about the diameter of a human hair, per second. There are 30 million seconds in a year (=3E7). So in a year, if it kept moving at this velocity, it would recoil 0.001 x 3E7 = 30,000 inches, which is about a half mile.

The asteroid makes a mess, but it stops. The energy is all turned to heat. What is heat? That's what we have to look at next.

Temperature. Even in a solid, the molecules are not at rest. They are in constant motion, but they don't get far. In a solid, they usually just shake around in between the other molecules. So their average motion is zero, but their instantaneous motion is always very high.

How fast? The typical instantaneous velocity of a molecule is comparable to the speed of sound. You may know the speed of sound from the old rule that you can measure the distance to lightning by counting seconds: 5 seconds for each mile. The light arrives very quickly, but it takes the sound 5 seconds to travel each mile. That is about 1000 feet per second, or 330 meters per second. Many people teach their children to count the seconds between the flash and the thunder, and that way to recognize that the lighting was far away. It makes the children feel better.

So the remarkable result is that the molecules and atoms in a solid, liquid, or gas, are in constant motion. At typical temperatures, the velocity is about 330 meters per second. Some go faster, and some go slower, but that is the typical velocity.

Is it a coincidence that the speed of molecules is approximately the speed of sound? No - because sound travels through air by molecules bumping into each other. So the speed of sound is determined by the speed of molecular motion.

The fact that the molecules are in motion is what gives us the sensation of temperature. When we touch something, we think it is warm if its molecules are moving faster than those in our hand. If they are moving slower, then we call it cold. When we cool something off, we are removing kinetic energy from those molecules, so they are moving slower.

We'll refer to the kinetic energy of shaking as "internal kinetic energy" because is it is not easily observed directly. An object at room temperature that is not moving, and appears to be at rest, has this violent shaking on the microscopic scale. But there are so many molecules present that the shaking tends to average out.

Discussion question: If you go to a high altitude, the temperature of the air is usually lower. What do you think that does to the sound velocity? This issue will turn out to be very important when we discuss UFOs, in a later chapter.

Temperature is usually measured on the Fahrenheit scale, the Celsius scale, or on the Absolute Scale. For physics purposes, the Absolute scale is the most useful. Here is how you convert from one to the other:

Fahrenheit to Celsius: subtract 32, then multiply the result by 5/9:

$C = (5/9)(F-32)$ (example: $F = 32$ is $C = 0$)

Celsius to Fahrenheit: multiply by 9/5, then add 32

$F = (9/5)C + 32$ (example: $C = 100$ is $F = 212$)

Celsius to Absolute: add 273

$K = C + 273$ (example: $C = -273$ is $K = 0$)

Historical digression on C and F. The original Fahrenheit scale was designed to make 0 F the coldest temperature that could easily be reached in a laboratory. That was done by mixing ice and salt, and that is what is called 0 F. The temperature of 100 F was chosen to be body temperature. (They made a slight mistake, and average body temperature is actually about 98.6F.) On this scale, water freezes at 32 F and boils at 212 F. When the centigrade scale was officially adopted (by the French, under Napoleon) they decided that the two standard points should be the freezing and boiling points of water. So water freezes at 0 C and boils at 100 C. Some people think the centigrade scale was more "metric" than the Fahrenheit scale, and that is ridiculous! Both were based on standard points 100 degrees apart; they just chose different standard points. The name of the centigrade scale was eventually changed to Celsius to honor Anders Celsius.

Amusing historical fact. Anders Celsius was a professor of Astronomy who built some of the world's best thermometers in the 1700s. He set up his scale to put 0 at the boiling point of water and 100 at the freezing point -- exactly backwards from the way we use it today. Higher temperature was colder!

The reason that the Absolute scale is most useful is that the absolute temperature is related to the internal random motion (the internal kinetic energy) of the molecules through a very simple law. If we have a given number of molecules (and for this purpose, we usually consider 1 mole of molecules, that is, 6 $\times 10^{23}$ molecules). Then the internal kinetic energy E is related to the temperature T by is:

$$T(K) = 335\ E(\text{Calories})$$

On a warm day, when T = 300 K = 27 C = 81 F, then E = 300/335 ≈ 1 Cal per mole. We'll show in a moment that a mole of TNT weighs 157 grams, so that 1 Cal per mole represents a small energy compared to the chemical energy of 157 Cal.

Note to physics majors. The equation for temperature may look unfamiliar, even if you have studied physics. In most physics texts, it is written in the following way:
E = (3/2) R T. I've just plugged in numbers for R, the "universal gas constant", and converted units to Calories.

That is an absolutely amazing and simple law. Ponder it for a few moments. Did you ever imagine that temperature would have such a simple meaning? The only really tricky part is that the temperature is on the absolute scale, and the energy must be measured for one mole of material.

Absolute zero. Absolute zero is defined as the temperature when all molecular motion stops. Actually, according to quantum mechanics, there still is a little motion even at absolute zero, but we'll ignore that. So at absolute zero, the kinetic energy (the energy of motion) of the molecules is zero. That's why you can't get below absolute zero. It is hard to have a velocity that is less than zero.

Review: what is a mole? A mole is an amount of material that has 6 $\times 10^{23}$ molecules in it. "Mole" is short for "gram molecular weight." Sometimes mole is abbreviated mol. (That saves a lot of ink.) If you know the chemical formula for the molecules, then it is easy to figure out how many grams you need for one mole. Just add up the atomic weights of the atoms in the formula. So, for example, if we have a piece of iron, then the individual molecules are iron atoms. Each iron atom has a mass of 56 (you can look this up on a periodic table). So one mole of iron weighs 56 grams. As another example, consider oxygen gas. Each molecule consists of O_2, i.e. two atoms of oxygen. Each oxygen atom has mass 16, so the combination has mass 32. So for one mole of oxygen gas, you need 32 grams. For carbon dioxide, each molecules has two oxygens (32) and one carbon (12) for a gram molecular weight of 44. So one mole of carbon dioxide weighs 44 grams.

TNT. Now let's think again about the explosive called TNT (trinitrotoluene). At normal room temperature, 20 C, the absolute temperature is T = 20 + 273 = 293. So using the formula for temperature, the internal random energy per mole is E = T/335 = 300/333 ≈ 1 Cal per mole. The formula for TNT is $C_7H_5N_3O_6$. Adding up the gram molecular weight:

7 carbons	84
5 hydrogens	5
3 nitrogens	42
6 oxygens	96
TOTAL	247

So the internal energy of 247 grams of TNT is 1 Cal, at room temperature. For one gram, it is 1/247 Cal. When TNT explodes, it suddenly releases 1 Cal per gram. That is 247 times as big as its previous amount. The internal kinetic energy suddenly increases by a factor of 247. If the molecules didn't break apart (they do - and that complicates it a little), the temperature would suddenly become 247 times greater. That would make the temperature 247 x 293 = 72,000 K. (Temperature measured in absolute scale is designated by K, rather than by C.) Note that we can convert back to Celsius: 72,000 K is approximately 72,000 C, since subtracting 272 from the number 72,000 is doesn't change it to the accuracy that we are using (rounding off to the nearest 1000).

Nothing is a solid at 72,000 C. The forces between the molecules are not strong enough to hold them together. Our gram of TNT is suddenly converted into a hot, a very very hot gas.

What will that hot gas do? Even at normal room temperatures, gases are typically 1000 times less dense than a solid. So just the fact that it turns into a gas makes it expand by a factor of 1000. But the fact that it is hot makes it expand even more. According to the ideal gas law, the volume is proportional to the absolute temperature (atmospheric pressure is constant). So the volume increases by a factor of 247 (the same factor we had for the temperature). Put that on top of the factor of 1000, and we get a total expansion in volume of 247,000.

That is what an explosion really is. A solid suddenly turns into a very hot gas, and the hot gas suddenly expands. The velocity of expansion is very high, since the atoms have all been given a very high velocity. The volume goes up, in this case, by 247,000.

Optional calculation: increase in linear size. When an object increase in volume by 247,000, how much does its size change? To work this out, and to make it easy, assume that the shape is that of a cube. Assume that our explosive has an initial volume of 1 cubic centimeter (=

1 cm^3), and that in the explosion its volume increases to 247,000 cm^3. What is the new side of the cube? The answer can be found by pushing the cube-root button on a calculator: 62.7 cm. You can check this answer from the fact that 62.7x62.7x62.7 = 157,000. This means that all the material in that one gram piece of TNT suddenly spreads out over a distance 62.7 times wider than the original piece.

The expanding gas pushes everything out of the way. Any material nearby picks up the velocity of the gas, and as that material is thrown out, it often does more damage than the hot expanding gas. Terrorists typically surround the explosive with a pipe, or pieces of metal. When the metal fragments fly out at high speed, they are what do the most harm. The military has built "fragmentation bombs" and "fragmentation grenades" based on the same principle. In the Vietnam War, some soldiers murdered their commanders with these grenades, giving rise to the expression of "fragging" them.

Interesting fact: Airbags literally explode open! The airbags that are used to protect you during a crash are balloons that inflate very rapidly, in a thousandth of a second, in between the time that the crash is detected by the automobile electronics, and the time that you would smash into the windshield. How can you fill a balloon that rapidly? The answer is, naturally, with an explosion. Airbags contain about 50 to 200 grams of an explosive called sodium azide. It has the chemical formula NaN_3. When triggered by an electric pulse, it decomposes into sodium metal and nitrogen gas. The released gas inflates the balloon.

Finally, the asteroid impact

A typical asteroid or comet will impact the Earth at a relative velocity of about 30 km/sec. When it hits, the Earth will recoil with one billionth of this velocity, a negligible amount. However the kinetic energy of the asteroid will be turned into heat.

Digression: calculate the energy We need the mass m of the asteroid. Whatever it is, the equivalent amount of TNT will be 100 times greater (since the asteroid is moving at 30 km/sec). Rock weighs about 3 tons per cubic meter (that's 3 times heavier than water). Let's assume the asteroid is a cube, with sides 10 km = 1E4 meters. Then the volume is 1E12 cubic meters. Each cubic meter is 3 tons, so the mass is 3E12 tons. The energy in tons of TNT equivalent is 100 times as big as this, so E = 3E14 tons of TNT.

Let's compare this to the world's nuclear arsenal. At its peak, there were about 30,000 warheads. Typical warhead explosive energy was 0.1 megatons of TNT. So the entire arsenal was 3000 megatons of TNT = $3x10^3$ megatons = $3x10^9$ tons of TNT. This is less than the asteroid energy by the factor $3x10^{14}/3x10^9 = 1x10^5$ = 100,000.

In the Nemesis book I gave a smaller number, but that was because I was assuming a smaller asteroid moving at a slower speed.

How hot will it get? A typical molecular velocity at room temperature (300K) is 330 meters per sec, the speed of sound. The asteroid is moving at 30 km/sec, i.e. 100 times faster than that. According to our equation, the energy is proportional to the square of the velocity: $100^2 = 10,000$. So the temperature (the internal kinetic energy) will be 10,000 times greater than 300 K, i.e. it will be T = 10000 x 300 = 3 million degrees.

What happens when this enormous energy is suddenly released? Much of the energy is transferred to the rock on the surface, which is also vaporized, liquefied, and expelled, making a crater that is 10 times larger across than the asteroid. We'll end this chapter with an extended quote from the book Nemesis:

Selection from book Nemesis (1987):

. . . Before a minute had passed, the expanding crater was 60 miles across and 20 miles deep. It would soon grow even larger. Hot vaporized material from the impact had already blasted its way out through most of the atmosphere to an altitude of 15 miles. Material that a moment earlier had been glowing plasma was beginning to cool and condense into dust and rock that would be spread world wide. The entire Earth recoiled from the impact, but only a few hundred feet. The length of the year changed by a few hundredths of a second.

The deep crater may have reached through the crust of the Earth to the mantle. The rock at this depth is very hot due to the natural radioactivity of trace amounts of potassium, uranium and thorium. The hot rock turned to liquid as soon as the weight of the rock above it had been removed. Great pressures from the earth's interior quickly filled in most of the crater with melted rock from below. . . .

Shock waves from the impact rattled the Earth with energy much greater than that of the largest earthquakes humans have experienced, probably a million times more energetic than the earthquake that devastated San Francisco in 1906. The shock may have triggered other earthquakes, causing aftershocks lasting for months or years. However this is speculation, for we don't know enough about the crust of the Earth to say with any certainty. Weak points in the earth's crust may have opened and sprouted new volcanoes. It is impossible to guess all the effects, or how long they lasted.

. . . If the asteroid did strike the ocean, it quickly punched through the water layer much as a rock would through a puddle, since in most places the depth of the ocean is less than the hypothesized 5 mile diameter of the asteroid. The splash created a great tsunami, or tidal wave, which grew hundreds of feet high as it swept towards shore. The giant wave swept around the Earth many times, inundating the coastal regions. The inner parts of the continents were spared.

Rock from the crater, mixed with vaporized comet material, cooled to several thousand degrees centigrade as it rose in a great fireball up through the atmosphere. It was then about as hot and bright as the surface of the sun, the greatest fireball ever seen by living creatures. But they didn't watch it for long, for the intense heat radiated from the glowing cloud burned everything within sight. The heat of the fireball also fused nitrogen and oxygen in the air to make nitrous oxides, a constituent of modern smog. Some of this gas would later combine with water in the atmosphere to make nitric acid. Likewise sulfur dioxide from burning plant material eventually formed sulfuric acid, which together with the nitric acid eventually fell to Earth. This acid rain may have been strong enough to dissolve the shells of creatures that lived near the surface of the oceans.

Some of the material ejected from the crater flew out of the atmosphere in ballistic trajectories and, like intercontinental ballistic missiles, rained havoc on distant continents. Some escaped into space, perhaps to hit the Earth on an anniversary of the impact when both the Earth and the ejecta returned to the same part of their orbits around the sun. As the fireball reached the top of the atmosphere it bobbed like a cork, floating on the cooler air beneath it, but it had nothing to hold it together and it began to spread out over the entire globe. As it spread, its color cooled from a glowing red to an impenetrable black. The surviving creatures below probably thought that night had come early. But it was a night without a moon, without stars. The dinosaurs could not see their own claws in front of their faces. Morning would not come for several months.

A few animals had avoided the initial destruction, and at first they seemed to manage surprisingly well. Most of the plant eaters could still find food, although the settling dust added a gritty taste to it all. Some of the carnivores were accustomed to hunting in the dark, although they had never experienced blackness such as this. But the ultimate source of all food, the sun, had been effectively blocked out. Without sunlight there was no photosynthesis, no creation of sugar and starch from carbon dioxide and water. Unseen by the creatures, the plants were turning from green to yellow, and then to brown. Except for the darkness, it would have been a beautiful autumn scene. The larger herbivores began to starve, followed soon afterwards by the large carnivores. Similar death occurred in the oceans. Phytoplankton, the first link in the food chain for the oceans, died from the acid rain and lack of sunlight, and the higher organisms quickly followed.

Without sunlight, the temperature of much of the Earth began to drop. On much of the land the temperature soon fell below freezing. Only those fortunate few animals that had already begun to hibernate didn't notice. Warm blooded creatures had an advantage in their ability to live with the cold, but they also required more food. Only the coastal regions had the cold moderated by the oceans, but these were the areas that had been devastated by the tsunamis. Tremendous storms were generated by the great temperature differences between the oceans and the land masses. The storms rained out the nitrous and sulfuric acids on to land and sea.

The tiny particles of dust began to stick to each other, agglomerating into larger particles that fell to Earth more quickly. All over the Earth the dust settled to form a layer about a half-inch thick. One day Walter Alvarez would puzzle over a section of this layer in an outcropping near Gubbio, Italy, where it had been brought up to the surface as the crust of the Earth folded during the creation of the Apennine mountains. Walter would cut a piece of it out to give as a gift to his father.

As the dust settled, sunlight began to filter through to the Earth's surface. Virtually every animal and plant had died. The plants were probably the first to revive. Many spores and seeds had been left behind. Life can be incredibly robust. For some plants the three month period of darkness and cold was no worse than a severe winter; these resprouted from seeds and roots. It was a miracle that any of the higher life forms made it through. Indeed virtually every land animal that weighed more than about 50 pounds had been extinguished, probably because they were most vulnerable in their high position on the food chain. The reptilian dinosaurs, both on land and on sea, had vanished forever. The nearest relatives of the dinosaurs to survive were the birds. We don't really know why. Perhaps it was their mobility, their ability to search for warmth and food. Perhaps they were better able than other dinosaurs to feed off decaying matter and seeds. Perhaps it was because they were warm blooded. We can't be sure, because we don't even know if the other dinosaurs were warm blooded or cold blooded. There was no obvious pattern that explained why certain creatures had survived, and others not. Life is both very robust, and yet very fragile.

With plant life suddenly sprouting all around, the few creatures that had made it through the catastrophe found themselves in a virtual Garden of Eden. Their natural enemies had been removed, and food from plants was abundant. However their species would not continue unless they could find mates. Those that could quickly spread out over the Earth, like (much more recently) the rabbits let loose in Australia. They filled the ecological niches that had been denied them by their previously "fitter" enemies. The slate of evolution had been wiped nearly clean. Now there was plenty of room for Nature to try new inventions. In fact, the great catastrophe was not only marked in the paleontological record by the disappearance of species, but also by the great proliferation of new species that followed. Like a forest fire clearing the brush, the destruction may have been necessary to clear the world of weak creatures who had nevertheless held on to a niche simply by virtue of being there first. In evolution, possession really is 9/10 of the law. The catastrophe had cleared out whatever stagnation there had been in the process of evolution. Once again there was room for free experimentation.

In this picture, evolution wasn't exactly what we had once thought it to be, creatures fighting other creatures to determine which one was best. To survive creatures also had to be adapted to endure catastrophe. Maybe that's why the mammals made it through. They had put up with trauma for 100 million years, the trauma of attempting to live with the dinosaurs.
