1

Introduction

Material is in motion all around us. Sometimes the relative motion leads to collisions, either accidental or intentional. The purpose of this book is to describe the mechanics of these collisions and the impact or penetration that follows, and to provide tools for determining the forces and deformation involved. Representative speeds of interest are shown in Table 1.1.

This book is an applied mechanics text, meaning it develops the mathematical tools in physics and engineering that are required to solve impact and penetration problems. Our primary interest is in solid materials. Since impacts can lead to large forces, there will be large deformations, and so our mathematical tools and our material models will address large deformation. A big step is understanding the stress tensor – the relationship of the stress tensor to the strain tensor contains information about the stiffness and strength (resistance to shear) of solids. We will explore how metals deform, flow, and break. We will explore how yarns and fabrics undergo large deflections. Modern armors are made from metals, ceramics, fabrics, explosives, and space. Armors are interesting in that they are designed to be as light weight as possible, and during an impact event the armor material is utilized through large deflection and deformation all the way to material failure (material separation).

The general framework we use is *continuum mechanics*. Continuum mechanics is the study of materials that can be viewed as a continuous material. This means that there is a smallest scale that it can reasonably address – on the order of tens of nanometers; otherwise atoms must be modeled. Our interest is typically in much larger scales, in macroscopic objects that are usually on the order of millimeters to meters. The basic equations of continuum mechanics will be developed – equations of conservation of mass, momentum, and energy. Then they will be applied. We will study waves in detail. All information in dynamic mechanical systems is conveyed through mechanical waves. In metals, the low pressure acoustical waves have a typical speed of 5 to 6 km/s, which is 15 to 18 times the speed of sound in air. High pressure shocks can travel faster than these acoustical waves.

In modern mechanics we have a threefold approach to understanding, namely experiments, analytical modeling, and large-scale numerical simulations. As a preliminary step, basic material tests are performed and the response of materials is either fit to analytic forms or stored in tables. The material response is typically referred to as equation of state and constitutive models. These material models are then used in analytical modeling and large-scale numerical simulations.

When it comes to applications to mechanics problems in impact and penetration, the analytical modeling approach makes assumptions about the geometry of the system response that reduce the problem to a handful of ordinary differential equations that are solved either explicitly or numerically. Large-scale numerical

Table 1.1. Impact speeds in nature and technology.

Origin	Speed	Comments
	(m/s)	
One-meter springboard	4.4	Drop $v = \sqrt{2gh}, \quad g = 9.8\ \mathrm{m/s}^2$
Human marathon	5.7	Dennis Kimetto, 42.195 km (26.2 mile) in 2:02:57 (2014)
Three-meter springboard	7.7	Drop
Human sprint	10.4	Usain Bolt, 100 m in 9.58 s (2009)
Ten-meter platform	14	Drop
Upward hull motion	5–15	Armored vehicle/buried explosive
Car speeds	27	Car collisions (60 mph)
Baseball fastball pitch	47.0	Aroldis Chapman, 105.1 mph (2010)
Paintball rounds	91	Serious eye injury (300 ft/s)
Bird strike (commercial)	154	Low-flying jets (300 knots)
Foam strike on *Columbia*	235	Loss of space shuttle (2003)
Jetliner cruise	246	550 mph (Mach 0.85)
Bird strike (military)	283	Low-flying jets (550 knots)
Sound speed in air	332	0°C
Handgun bullets	350–450	Handguns have short barrels
N_2 gas molecule speed	510	Average in air at 20°C
Waterjet speed	750	In metal-cutting machines
Rifle bullets	750–950	Rifles have long barrels
	(km/s)	
Anti-tank rounds	1.2–1.6	KE projectiles fired by tanks
Sound speed in water	1.48	
Warhead fragment speeds	1–2	
Explosively formed pen.	2.5–3.0	EFPs invert, not collapse
Shear wave speed in metals	2.5–3.2	Transverse wave c_s
Sound speed in metals	5–6	Longitudinal wave c_L
Missile defense closing rate	7	Midcourse intercept
Low Earth orbit speed	7.5	Leads to orbital debris impacts
Shaped-charge jet tip	8–12	Stagnation point collapse
Earth escape velocity	11.2	Minimal meteor strike
Cassini flybys of Enceladus	5–18	Ice grain impacts
Chelyabinsk meteor	19	Blast damage in Russia (2013)
Earth orbit around sun	29.8	Meteor speeds
Solar escape velocity	42.1	From 1 AU; comet speeds
Jupiter escape velocity	60	Shoemaker–Levy 9 comet strike, fastest recorded large impact (1994)

simulations are computations where the materials and/or space are discretized into a large number of computational cells or elements and the partial differential equations of mass, momentum, and energy conservation are numerically solved. The distinction between the two modeling techniques will become clear as we develop analytical models and compare their results to those of both experiments and large-scale numerical computations. The three approaches – experiments, analytical

Cambridge University Press
978-1-108-49710-7 — Modern Impact and Penetration Mechanics
James Walker
Excerpt
More Information

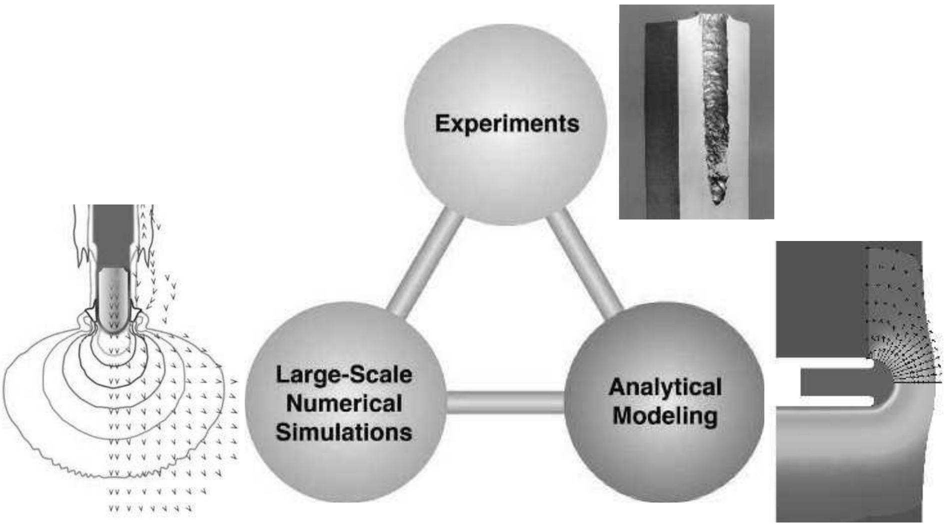

FIGURE 1.1. Three-fold approach to understanding: experiments, large-scale numerical simulations, and analytical modeling.

modeling, and large-scale numerical simulations – work towards an understanding of impact and penetration events (Fig. 1.1). A particular comment about analytical modeling: it is an important part of understanding physical phenomena since development of analytical models requires the assumption of certain physical processes. Therefore, if an analytical model matches the experimental results over a wide range of, say, impact velocities, then the relevant physics has been included in the model and the physical mechanisms governing the event are understood. Large-scale numerical simulations are able to address complicated geometries and complicated material models. As computational speeds have increased, storage costs have come down, and as parallelization has been embraced, powerful computational tools have become widely available. Graphics technology now produces beautiful images and movies of simulated impact and penetration events.

In this book experimental data, which are the final arbiter of truth, are presented both for their own sake and for direct comparison to models.

1.1. Launchers

There are two primary techniques used to launch impactors to high speeds in a research environment. The first technique is through the expansion of a high-pressure gas and the second technique is through electromagnetic force. The expansion of a gas technique relies on the fact that, as a gas expands, its pressure does not drop very much. Hence, as expansions get larger in the launch tube, significant pressures are still applied to the back of the launch package so that it continues to accelerate. Such behavior can be contrasted with liquids, where a high fluid pressure quickly drops with expansion. The reason why the electromagnetic approach works is because the electromotive force can be applied over a significant distance.

Low speed launchers in a research environment are simply a pressure vessel, a fast acting valve, and a launch tube or gun barrel. The projectile is placed near

Cambridge University Press
978-1-108-49710-7 — Modern Impact and Penetration Mechanics
James Walker
Excerpt
More Information

TABLE 1.2. Laboratory launcher speeds in study of impact and penetration.

Launcher	Speeds (km/s)	Comments
Leading edge of SHPB	0–0.12	Split-Hopkinson pressure bar
Compressed gas gun	0–0.3	Air or nitrogen as driving gas
Compressed gas gun	0–1.0	Hydrogen as driving gas
Powder gun	0.2–2.1	Propellant gases drive projectile
Rocket powered sled	0.5–3	Extended rail track to guide sled
Electromagnetic rail gun	1–4.5	Current through contact armature
Laser launched flyer	0.7–6.0	Spalled by laser pulse
Explosively launched flyer	2–6.5	Explosive lens launched plate
Large two-stage light gas gun	2–7	50 gram, 2 to 4 cm diameter
Small two-stage light gas gun	2–10	50 milligram, 2 to 4 mm diameter
Inhibited shaped charge	8–12	1-gram fragments
Three-stage gun	9–14	Two-stage gun with spall pillow
Magnetically launched flyer	15–44	Huge electric currents
Nuclear explosive launched flyer	30–60	No longer available

the valve at the rear of the barrel. The pressure vessel is taken to a high pressure. The valve is opened and the projectile is accelerated down the barrel. The speed at which the gas drives the projectile is limited by the sound speed of the gas, because if the projectile moves faster than the sound speed, information about the fact that the projectile has moved on cannot be communicated to the gas, so it cannot move to apply pressure to the back of the projectile. In the laboratory, typically air or nitrogen is used as the gas to propel projectiles up to around 300 m/s. If higher velocities are required, helium or hydrogen is used. Since the sound speed of a gas is given by $\sqrt{\gamma p/\rho}$ (this formula will be derived later in the text), going from N_2 of molecular weight 28 to H_2 of molecular weight 2 increases the sound speed by a factor of $\sqrt{14} = 3.74$, allowing speeds of around 1,100 m/s to be reached. A large gas gun that has barrel diameters of up to 30 cm is shown in Fig. 1.2. This gas gun has been used to launch bird carcasses and simulants for aircraft certification and turbine blades and pieces of rotors for containment studies (i.e., containment of parts after an aircraft, train, or power turbine fails, to ensure the safety of nearby people). It was also used to launch insulating foam into a wing leading edge test fixture during the space shuttle *Columbia* accident investigation.

The next step up in speed is accomplished by using a solid or liquid propellant or gun powder to produce the gas. In these guns, there is a breech attached to a barrel. The powder is placed in the breech and ignited. As the powder or propellant burns, it transitions to a gas, which is hot. It is confined and large pressures result. The expanding gas then pushes the launch package down the barrel. This is the way most firearms work, where the cartridge holds the gunpowder, a primer on the bottom (which produces a spark or flame when struck to ignite the powder), and a bullet at the top, held to the cartridge with a crimp, to ensure the powder burn reaches an appropriate level before releasing the projectile (the “fast-acting valve”). A powder gun from the laboratories at Southwest Research Institute (SwRI) is shown in Fig. 1.3. The 50-mm powder gun has launched projectiles up to 2.1 km/s. The propellant is placed in the breech and a “spit tube” is used to extend the

FIGURE 1.2. The large gas gun at SwRI. A cylindrical pressure vessel is to the left, followed by a fast-acting valve, followed by a long barrel. This photograph was taken before an impact test against the space shuttle leading edge test article, July 2003. High-speed cameras and lights surround the target.

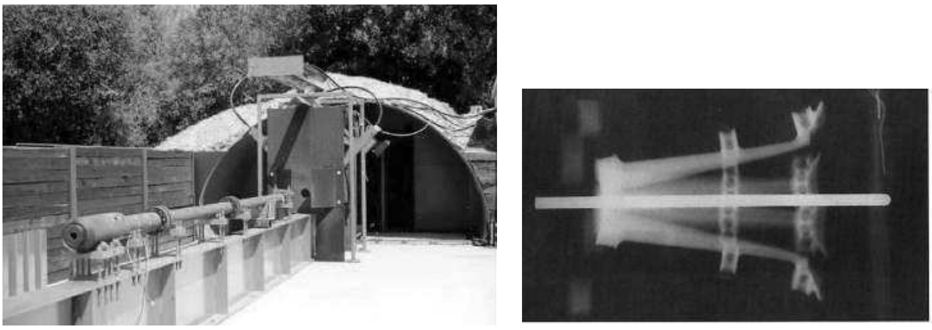

FIGURE 1.3. Left: 50-mm powder gun at SwRI. The breech is to the left; orthogonal flash X-ray heads are near the target. Right: A flash X-ray of a launch package shot from the gun at 1.5 km/s, comprising a threaded tungsten projectile held by a four-petal aluminum sabot, which is opening up and separating owing to aerodynamic drag (the launch package is moving left to right).

initiation sparks the full length of the propellant. High-velocity shots launching 400-gram launch packages to 2 km/s take about 1,300 grams of a modern propellant or gun powder. The pressure in the breech reaches 350 MPa.

The next step up in speed is accomplished by using two stages. The first stage is a powder gun, which launches a polyethylene piston to compress a gas for the second

Cambridge University Press
978-1-108-49710-7 — Modern Impact and Penetration Mechanics
James Walker
Excerpt
More Information

FIGURE 1.4. Large two-stage light gas gun at SwRI during assembly. The high pressure powder breech is to the left; the pump tube is in two parts; the high-pressure section connector is missing. Then come the launch tube and finally the evacuated target chambers. The gun can launch 60 grams to 7 km/s.

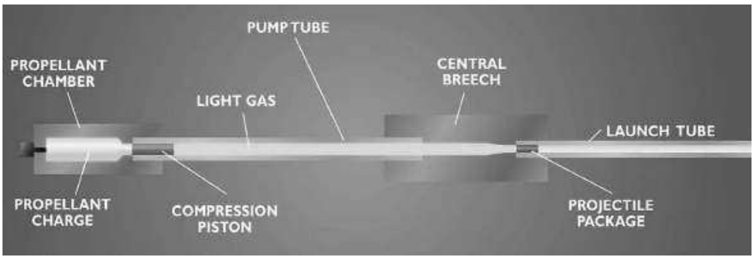

FIGURE 1.5. Two-stage light gas gun schematic.

stage. The piston speed is not particularly high (up to 1 km/s), but it is massive and can compress the gas in the second stage. The second stage gas is typically hydrogen because that is the gas with the highest sound speed. It is compressed to pressures of 800 MPa and temperatures of 1,750 K in the high-pressure coupling section. High temperatures are important, because temperature controls the sound speed in the gas (Exercise 5.17). Also, the light gas is in motion, so that the sound speed is augmented by the speed of the gas. The fast-acting valve, in this case, is a disk of steel that has been scored with an X to different depths so that it fails and peels back, opening up to allow the compressed hydrogen gas to drive the launch package. Speeds in these two-stage light gas guns, as they are called, can reach 7 to 10 km/s, depending on the diameter of the barrel or launch tube. The large two-stage light gas gun at SwRI is shown in Fig. 1.4, with a schematic in Fig. 1.5. It has a 38-mm diameter, 10-meter long launch barrel and a 11.4-cm diameter, 9-meter long pump tube. Before shots, the barrel, flight chamber, and target chambers are evacuated, typically to a pressure of 5 to 20 Torr. The burst

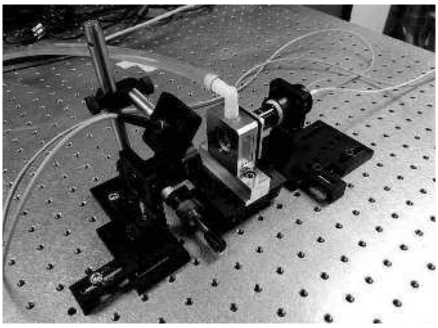

FIGURE 1.6. Laser-launched flyer arrangement at SwRI. Laser pulse comes in from the left through the lens into the evacuated chamber. Fibers to right are the particle displacement velocimetry (PDV) laser measurement system for measuring particle velocity on back surface of target.

disk is part of the pressure seal. The high-pressure steel coupling, where the larger diameter pump tube is gradually reduced to the small diameter launch tube, has an outer diameter of 56 cm and a length of 97 cm, and weighs 1,800 kg.

The next step up in speed is accomplished by placing a graded-density plate or pillow at the muzzle end of the two-stage light gas gun. A graded-density impactor then strikes the plate or pillow, and a high-pressure stress wave transits the pillow and reflects off the free surface. When it returns in the direction of the gun and meets the reflected wave off the back of the projectile, it launches some of the plate or pillow (see Section 4.10 for a description of this spall process). Speeds achieved by this process have been 9 to 14 km/s. In this case, the projectile is typically a flat flyer plate. This is called a three-stage light gas gun. It marks the end and upper limit of what has been accomplished so far with pressure-gun technology.

There are other ways to produce high-pressure gases beyond burning and compressing. A fast laser pulse can vaporize material and, when placed in contact with a thin flyer, like aluminum foil, it can launch the flyer. Figure 1.6 shows the set-up from SwRI's laser lab. Launch speeds of 6 km/s have been achieved with this technique, but the mechanism is the same – a high-pressure gas is produced that then drives a flyer. In this case the flyer is thin and the confinement and short "barrel-like" behavior is produced by nearby material through the localization of the laser pulse.

In some ways the National Ignition Facility at Lawrence Livermore National Laboratory uses this technique to compress deuterium and tritium fuel pellets for fusion studies. Huge banks of high-powered lasers provide a pulse that produces high-energy X-rays that penetrate a thin layer on the outside of the fuel pellet. The layer vaporizes, which then drives the spherically shaped surface inward, producing very high pressures in a spherical compression. Collapse speeds of 350 km/s have been reported.

Finally there is one other approach, and that is to use electromagnetism. In this case, a current flows through a closed circuit. The launch package has an armature that touches two rails. Current flows around this loop, producing a magnetic field that wants to expand. The expansion accelerates the projectile touching the rails. These rail guns, as they are called, require a high-power electrical storage source that can unload of its energy quickly. This is done mechanically – for example, by rapidly stopping a flywheel (homopolar generator) or through capacitor banks. Speeds for rail guns have been reported at 6 km/s. A large struggle with rail guns is that the projectile needs to maintain good contact with the rails to maintain the electrical current. This leads to gouging of the rails at high speeds, greatly limiting their life span. To date, however, the focus on rail guns has been their development; they have not been used where the focus was impact studies.

The next step in electromagnetic driving has been accomplished with the Z-machine at Sandia National Laboratories. Here a huge machine provides a charge of 6 million amps over a short time span, which produces motion in flyers due to magnetic forces. These forces have launched flyer plates up to 44 km/s [**20**]. There is a smaller laboratory device based on the same principle.

Electrostatic launchers are used to launch dust. Here, in a vacuum, micron-sized dust particles are ionized and a voltage potential is applied across separated, perforated plates to accelerate the dust, similar to a cathode ray tube. The dust particles can reach tens of kilometers per second, but they are very small.

1.2. Launch Packages

In research settings, most launches occur with sub-caliber impactors or projectiles, meaning that the projectile diameter is less than the diameter of the barrel. The projectile is held in a *sabot*, which is the French word for clog or outer shoe with a thick wooden sole. The sabot is the diameter of the barrel and provides the pressure seal with the barrel. In particular, the sabot produces a full-barrel cross sectional area footprint for the driving force on the launch package, thus allowing sub-caliber high-density projectiles to be launched. The sabot can also provide structural support to the projectile or impactor, to prevent buckling of long projectiles, for example. When the launch package exits the gun barrel (the launch end of the gun is called the muzzle), the sabot is separated from the projectile. This is accomplished in several fashions. First, aerodynamic drag on the sabot petals causes them to separate from the projectile and fly on a different trajectory. Typically the projectile will fly through a hole in what is called a stripper plate; the sabot petals strike this plate, as they don't fly through the hole, and are stopped. Second, a rifled barrel (meaning there are spiral scores in the interior sides, to impart a spin during launch) so that the launch package emerges with a rotational velocity that separates the sabot from the projectile. Third, for lower speed launches it is possible to have a constricting cage attached to the muzzle, so that the sabot is decelerated and stopped by its interaction with the cage and the projectile continues on. An X-ray of an aluminum sabot separating from a cylindrical tungsten alloy projectile is shown in Fig. 1.3.

Sometimes a sabot cannot be efficiently separated from the projectile. For example, when we launch foam in our labs we do not use a sabot, but produce a specialty barrel for each foam cross section of interest.

1.3. Diagnostics

Historically the main diagnostics in impact and penetration mechanics have been flash X-rays, shorting pins, strain and pressure gages, and laser interferometry

Cambridge University Press
978-1-108-49710-7 — Modern Impact and Penetration Mechanics
James Walker
Excerpt
More Information

techniques (VISAR and PDV) to measure speed or displacement of a point on a surface. However, the world of diagnostics is being overtaken by fast electronic optical cameras and digital image correlation. These cameras and software tools allow a determination of the displacement of a surface at various points in time. Very fast cameras can record at a rate of millions of frames per second, though typically such cameras have a limited number of frames, such as 16, as the speed is achieved by each electronic image plane only recording one or two images. Slower cameras with "unlimited" numbers of frames, where the electronic image plane is stored and reset for each recorded frame, can run at speeds up to 100,000 frames per second (and faster for reduced image size).

1.4. Nonlinearities and Confinement

A theme of this book is explicitly addressing and quantitatively computing nonlinear response. We will see a variety of origins and results of nonlinearity:

1. When solid materials undergo large compressions, the pressure vs. volumetric strain is nonlinear. At small strains, it is linear, but at large strains it exhibits higher order terms that greatly increase the pressure and limit further compression.
2. The nonlinear compressive response gives rise to impulsive loads forming shocks in the material, where the shock speed is supersonic with respect to the ambient sound speed of the material. A shock is a discontinuous change in material properties across a moving propagation front.
3. When a material is compressed by a shock wave, not only does lattice compression occur, but energy is deposited in the material. This leads to thermal motions of the atoms, which in turn leads to additional stress. Thermal motion leading to additional stress is due to nonlinearity in atomic interactions.
4. Metals begin to plastically deform when their yield stress is exceeded. At small stress and before yield, the stress-strain response of metals is elastic and linear, but when the stress is large enough yield occurs and the subsequent response is nonlinear. Modeling with this nonlinear strength response is central to predicting penetration events.
5. In one-dimensional penetration events, nonlinearity of the target material can produce the surprising result that deforming impactors penetrate more deeply than nondeforming impactors.
6. The nonlinear stress–strain response of materials gives rise to a two-wave structure in shock waves at lower pressures. There is a fast running elastic precursor followed by the wave front where plastic deformation occurs.
7. Large motions lead to acceleration having a significant nonlinear term due to advection. This nonlinearity is the origin of inertial stress terms in penetration resistance.
8. For metals, higher strength typically implies smaller failure strain, and this reciprocal relationship between strength and failure strain produces interesting results in finite target penetration.
9. Liberation of material during cratering has nonlinear size scaling and exhibits a transition in size scale behavior indicative of the saturation of a damage process.

(10) Yarns and fabrics undergo small strains but large rotations in impact events and their effectiveness in stopping impactors is through large deflections. When materials undergo large rotation, it is necessary to use large strain formulations that are nonlinear to model the behavior.

(11) Rubber-like materials have, for low pressures, relative incompressibility and nonlinear response at large strains, which leads to experimentally observed nonuniqueness and bifurcation of solutions.

All these behaviors are interesting. We will pursue them to obtain explicit expressions and fully understand the origin and effects of the various terms.

Another factor that has a large influence on impact and penetration events is confinement. Confined motions lead to higher stresses. One-dimensional motion is highly confined and leads to strong shocks. Sometimes the confinement is provided by boundary conditions, sometimes by impact geometry, and sometimes by inertia. Stresses are lower in penetration events than in one-dimensional impact events since the confinement is less and material is able to move laterally, out of the way of the projectile. Of course, there is some lateral confinement resisting the motion, and the details of how the material moves and the material's constitutive response will allow us to explicitly compute the resistance to penetration.

1.5. Sources

Some other books that address impact and terminal ballistics – that is, what happens when projectiles impact targets (as opposed to interior ballistics and exterior ballistics, which discuss projectile motion inside a gun and in flight, respectively) – are the monograph *Impact* by Goldsmith [**77**], and the collections of survey chapters in *High Velocity Impact Phenomena* [**119**], *Impact Dynamics* [**219**], *High Velocity Impact Dynamics* [**218**], the Springer series *High-pressure Shock Compression of Solids I – VIII* [**21, 37, 53, 72**], *Dynamic Behavior of Materials* by Meyers [**147**], Rosenberg and Dekel's *Terminal Ballistics* [**165**], Grady's *Physics of Shock and Impact* [**81**], and the SwRI Penetration Mechanics Short Course notes [**18**].

There are three major conferences held in impact and penetration, with corresponding professional societies and published proceedings. The International Symposium on Ballistics is held every 18 months. It began in 1974 and falls under the auspices of the International Ballistics Society. The Hypervelocity Impact Symposium has occurred in two spurts. The first was from 1955 to 1969 where there were 8 symposia. With the success of the Apollo missions, interest waned. A new series of Hypervelocity Impact Symposia began in 1986, spurred by the Strategic Defense Initiative for ballistic missile defense. That series is still running, held every two or three years, and many of its proceedings have appeared in the *International Journal of Impact Engineering.* The American Physical Society has a topical group in the Shock Compression of Condensed Matter that meets every other year. Participation in one of these or related symposia is highly recommended for anyone interested in the field of impact and penetration. These three offer competitive incentives for students that cover conference registration fees and some travel expenses.

Exercise

(1.1) Look up when the three symposia mentioned in the text next occur. What are the details of their student programs? When are applications due?