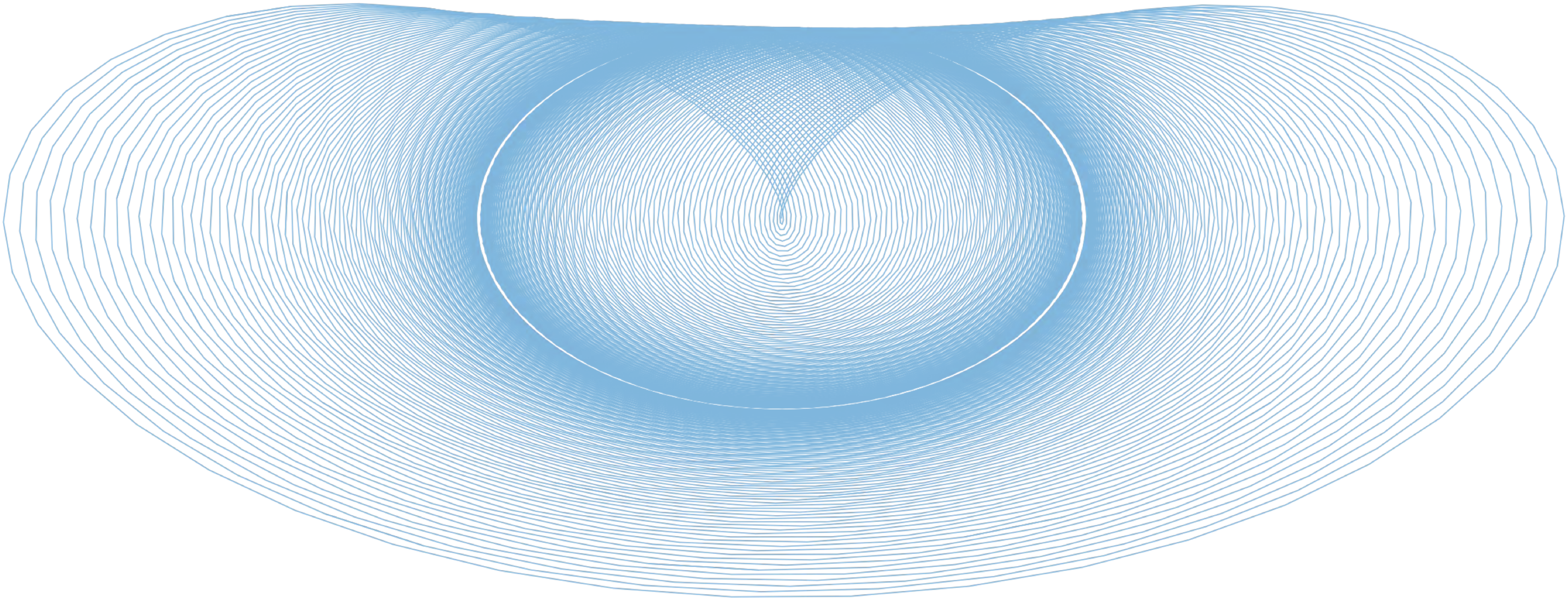
PHYS 1420 (F19)
Physics with Applications to Life Sciences



2019.11.06

Relevant reading:

Kesten & Tauck ch. 8.7

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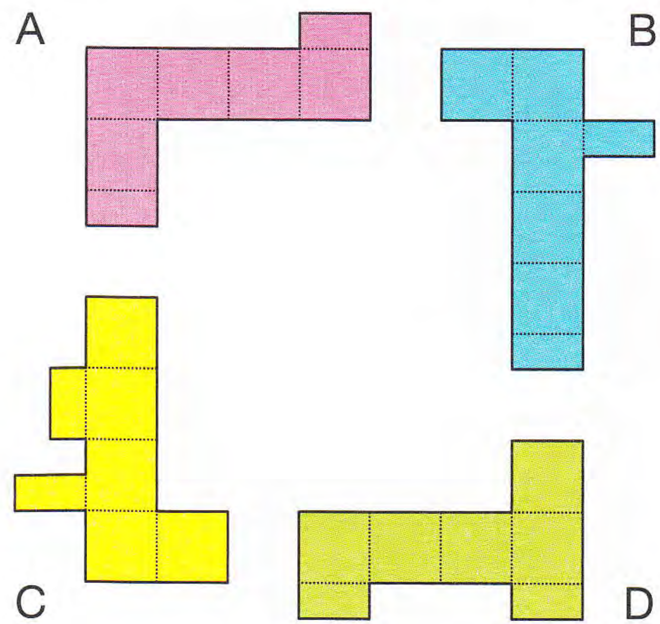
Ref. (re images):
Wolfson (2007), Knight (2017),
M. George, Kesten & Tauck (2012)
Resnick & Halliday (1966)

72. L-Rectangle Cube



Which pattern forms a full cube when folded along the dotted lines? No parts of the patterns should overlap when folded.

A B C D

Announcements & Key Concepts (re Today)

→ Written HW #2: Posted and due Friday 11/15 in class

→ Midterm exams: Grades posted on Moodle and exams to be handed back...

Some relevant underlying concepts of the day…

- Angular momentum
- Angular version of Newton's 2nd Law
- Conservation of angular momentum
- Extensions beyond classical physics → MRI

Comparison summary

TABLE 4.1 Rotational and linear kinematics for constant acceleration

Rotational kinematics	Linear kinematics
$\omega_f = \omega_i + \alpha\,\Delta t$	$v_{fs} = v_{is} + a_s\,\Delta t$
$\theta_f = \theta_i + \omega_i\,\Delta t + \frac{1}{2}\alpha(\Delta t)^2$	$s_f = s_i + v_{is}\,\Delta t + \frac{1}{2}a_s(\Delta t)^2$
$\omega_f^2 = \omega_i^2 + 2\alpha\,\Delta\theta$	$v_{fs}^2 = v_{is}^2 + 2a_s\,\Delta s$

Rectilinear Motion		Rotation about a Fixed Axis	
Displacement	x	Angular displacement	θ
Velocity	$v = \frac{dx}{dt}$	Angular velocity	$\omega = \frac{d\theta}{dt}$
Acceleration	$a = \frac{dv}{dt}$	Angular acceleration	$\alpha = \frac{d\omega}{dt}$
Mass	M	Rotational inertia	I
Force	$F = Ma$	Torque	$\tau = I\alpha$
Work	$W = \int F\,dx$	Work	$W = \int \tau\,d\theta$
Kinetic energy	$\frac{1}{2}Mv^2$	Kinetic energy	$\frac{1}{2}I\omega^2$
Power	$P = Fv$	Power	$P = \tau\omega$
Linear momentum	Mv	Angular momentum	$I\omega$

→ Now we come to that last bit: *Angular momentum*

Resnick & Halliday

Rotational Dynamics

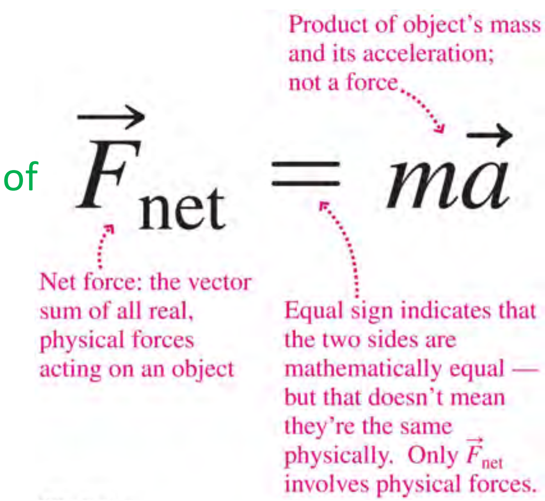
Torque = "Force analog"

$$\vec{\tau} = \vec{r} \times \vec{F}$$

Now what if all the torques don't add up to zero?

$$\sum_i \tau_i = \sum_i r_i F_i = 0.$$

Think along the lines of rotational analog of Newton's 2nd



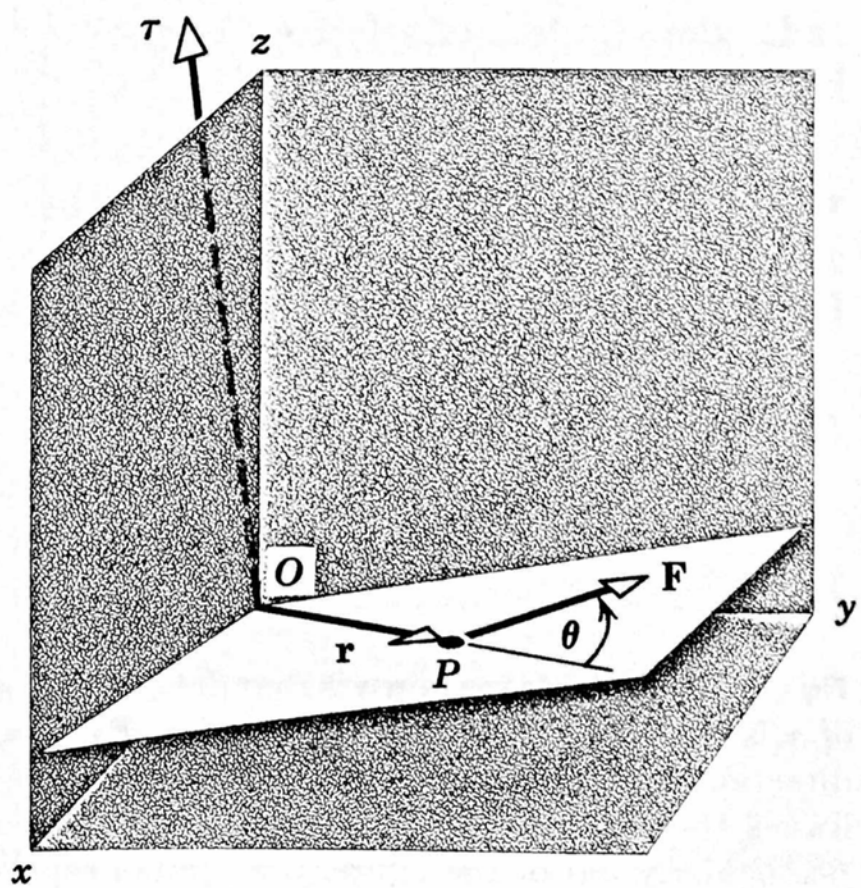


Fig. 12–1 A force **F** is applied to a particle *P*, displaced **r** relative to the origin. The force vector makes an angle *θ* with the radius vector **r**. The torque **τ** about *O* is shown. Its direction is perpendicular to the plane formed by **r** and **F** with the sense given by the right-hand rule.

Resnick & Halliday

Rotational Dynamics

→ All the bits and pieces we have developed thus far will come into play (e.g., conservation of momentum, moments of inertia, etc...)

Product of object's mass and its acceleration; not a force

$$\vec{F}_{net} = m\vec{a}$$

Net force: the vector sum of all real, physical forces acting on an object

Equal sign indicates that the two sides are mathematically equal — but that doesn't mean they're the same physically. Only $\vec{F}_{net}$ involves physical forces.

Reminder:

Law of conservation of momentum The total momentum $\vec{P}$ of an isolated system is a constant. Interactions within the system do not change the system's total momentum.

Linear momentum

$$\vec{p} = m\vec{v}$$

Angular momentum

(defined as)

$$\vec{L} = I\vec{\omega}$$

$$\vec{L} = \vec{r} \times \vec{p}$$

Connection to Newton's 2nd

$$\vec{F} = \frac{d\vec{p}}{dt}$$

"Rotational Newton's 2nd "

$$\vec{\tau} = \frac{d\vec{L}}{dt}$$

Angular momentum is conserved when all torques add up to zero

Rotational Dynamics

Let us derive this relationship $\vec{\tau} = \frac{d\vec{L}}{dt}$

$$\vec{F} = \frac{d\vec{p}}{dt}$$

Definition of torque

$$\vec{\tau} = \vec{r} \times \vec{F}$$

$$\mathbf{r} \times \mathbf{F} = \mathbf{r} \times \frac{d\mathbf{p}}{dt}. \quad \rightarrow \quad \boldsymbol{\tau} = \mathbf{r} \times \frac{d\mathbf{p}}{dt}.$$

Now we differentiate
(definition of angular momentum re time)

$$\vec{L} = \vec{r} \times \vec{p} \quad \rightarrow \quad \frac{d\mathbf{l}}{dt} = \frac{d}{dt}(\mathbf{r} \times \mathbf{p}).$$

Chain rule applies!

$$\frac{d\mathbf{l}}{dt} = \frac{d\mathbf{r}}{dt} \times \mathbf{p} + \mathbf{r} \times \frac{d\mathbf{p}}{dt}.$$

Now $d\mathbf{r}/dt$ is just the inst. velocity $\mathbf{v}$

$$\frac{d\mathbf{l}}{dt} = (\mathbf{v} \times m\mathbf{v}) + \mathbf{r} \times \frac{d\mathbf{p}}{dt}.$$

The velocity $\mathbf{v}$ is in the same direction as the momentum $m\mathbf{v}$
(thus the cross product is zero)

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Rotational Dynamics

Let us derive this relationship $\vec{\tau} = \frac{d\vec{L}}{dt}$

$$\frac{d\mathbf{l}}{dt} = (\mathbf{v} \times m\mathbf{v}) + \mathbf{r} \times \frac{d\mathbf{p}}{dt}.$$

$$\frac{d\mathbf{l}}{dt} = \mathbf{r} \times \frac{d\mathbf{p}}{dt}.$$

$$\boldsymbol{\tau} = d\mathbf{l}/dt,$$

(or in English)

The time rate of change of angular momentum of a particle is equal to the torque acting on it

$$\tau_x = (dl/dt)_x \qquad \tau_y = (dl/dt)_y, \qquad \tau_z = (dl/dt)_z.$$

Scalar equivalents...

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A familiar (non-rotational) example...

A particle of mass m is released from rest at point a in Fig. 12–4, falling parallel to the (vertical) y-axis. (a) Find the torque acting on m at any time t, with respect to origin O. (b) Find the angular momentum of m at any time t, with respect to this same origin. (c) Show that the relation $\boldsymbol{\tau} = d\mathbf{l}/dt$ (Eq. 12–7) yields a correct result when applied to this familiar problem.

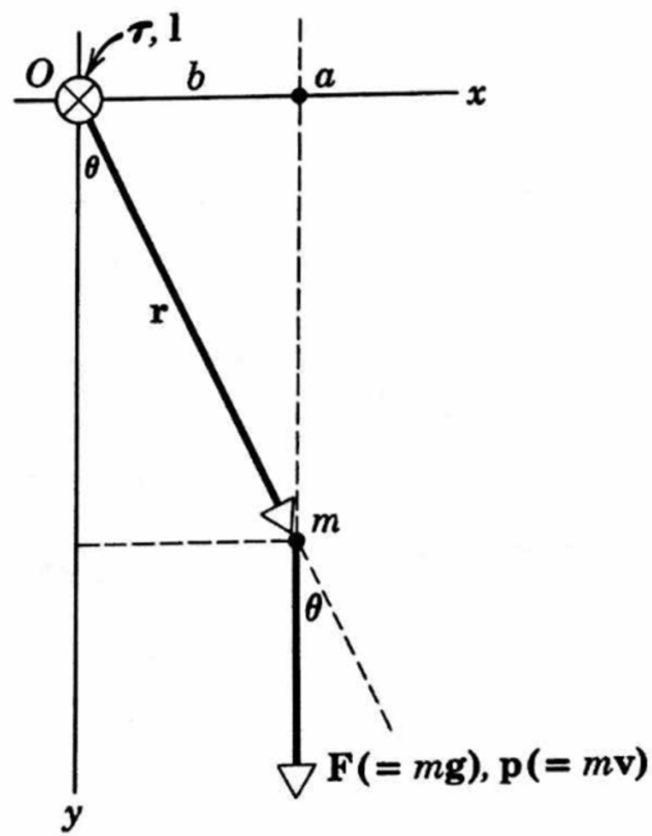

Fig. 12–4 A particle of mass m drops vertically from point a. The torque and the angular momentum about O are directed perpendicularly into the figure, as shown by the symbol ⊗ at O.

Note: This is not a rotational problem per se, but that doesn't mean we can not treat it using our tools thus far developed...

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A familiar (non-rotational) example...

Torque: $\vec{\tau} = \vec{r} \times \vec{F}$ $\tau = rF \sin \varphi$

Here: $r \sin \theta = b$ and $F = mg$

$\tau = mgb =$ a constant.

Torque goes into the page

Note that torque is simply the product of mg and the "*moment arm*" (b)

Angular momentum: $\mathbf{l} = \mathbf{r} \times \mathbf{p},$ $l = rp \sin \theta.$

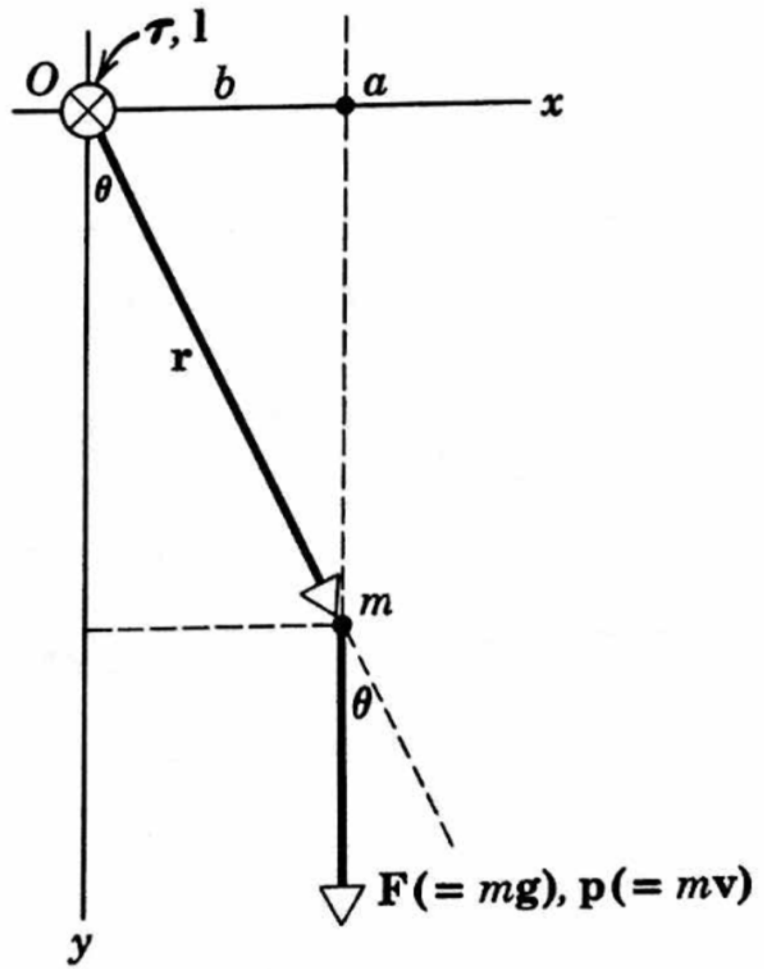
Here: $r \sin \theta = b$ and $p = mv = m(gt)$

$l = mgbt.$

Ang. momentum also goes into the page, but magnitude increases w/ time

$\boldsymbol{\tau} = d\mathbf{l}/dt,$ $mgb = \frac{d}{dt}(mgbt) = mgb,$

As expected!



Note that if we drop the b terms on both sides... $mg = \frac{d}{dt}(mv)$

$\vec{F} = \frac{d\vec{p}}{dt}$ ... which just leads back to Newton's 2nd

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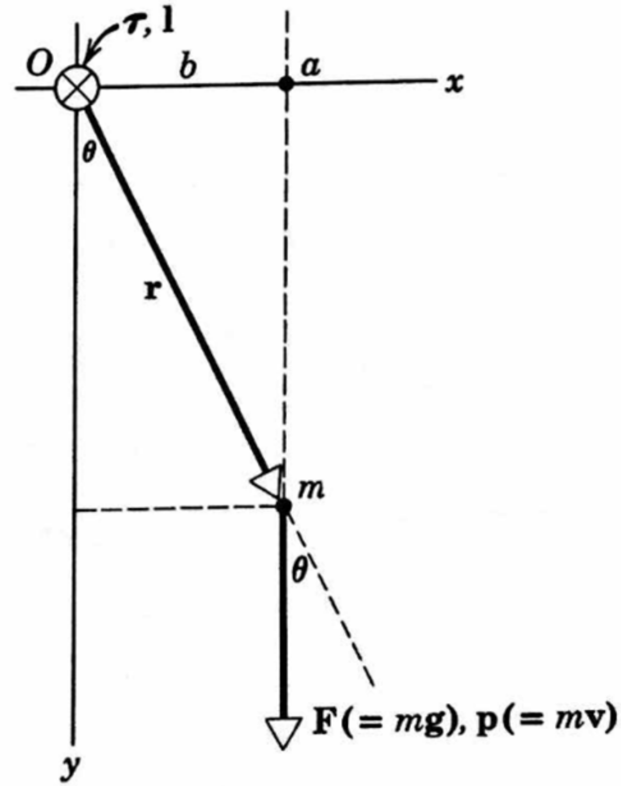
A familiar (non-rotational) example...



Thus, as we indicated earlier, relations such as $\boldsymbol{\tau} = d\mathbf{l}/dt$, though often vastly useful, are not new basic postulates of classical mechanics but are rather the reformulation of the Newtonian laws for rotational motion.

Note that the values of τ and l depends on our choice of origin, that is, on b. In particular, if $b = 0$, then $\tau = 0$ and $l = 0$. ◀

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Conservation of Angular Momentum

Assumption: We are talking about an inertial reference frame

$$\boldsymbol{\tau}_{\text{ext}} = d\mathbf{L}/dt.$$

Time rate of change of total angular momentum of a system of particles about a fixed point is equal to the sum of *external* torques acting on it

Suppose now that $\boldsymbol{\tau}_{\text{ext}} = 0$; then $d\mathbf{L}/dt = 0$ so that $\mathbf{L}$ = a constant.

When the resultant external torque acting on a system is zero, the total vector angular momentum of the system remains constant. This is the *principle of the conservation of angular momentum.*

When the resultant external torque on the system is zero, we have

$$\mathbf{L} = \text{a constant} = \mathbf{L}_0,$$

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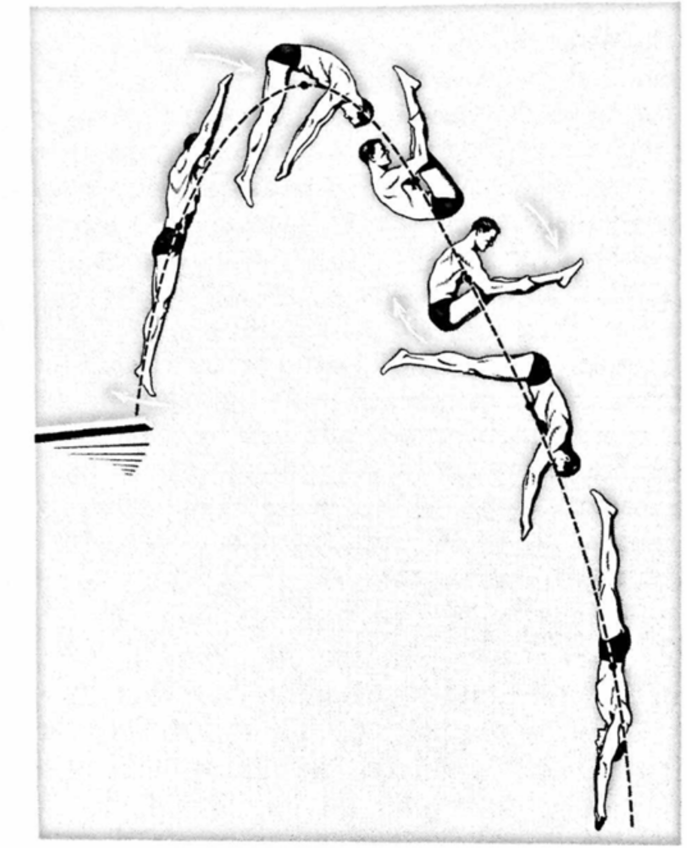
Conservation of Angular Momentum

Consider a "rigid body" rotating about a fixed axis. Then: $\vec{L} = I\vec{\omega}$

Conservation of angular momentum then implies: $I\omega = I_0\omega_0 = \text{a constant.}$



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Ex. (re conservation of angular momentum)

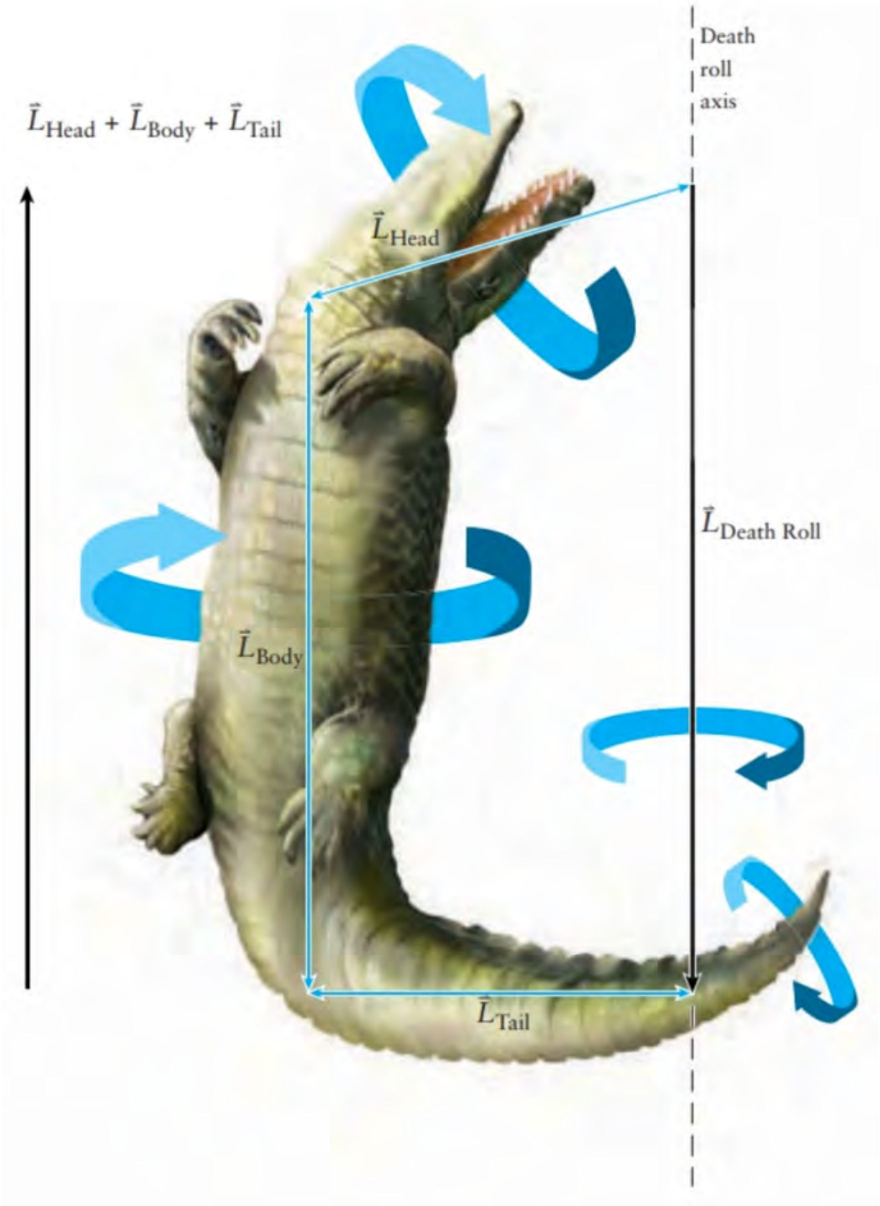
A spinning figure skater starts from an initial angular velocity of $\omega_i = 12[\text{rad/s}]$ with her arms extending away from her body. In this position, her body's moment of inertia is $I_i = 3[\text{kg m}^2]$. The skater then brings her arms close to her body, and in the process her moment of inertia changes to $I_f = 0.5[\text{kg m}^2]$. What is her new angular velocity?

This is a job for the law of conservation of angular momentum:

$$L_i = L_f \qquad \Rightarrow \qquad I_i\omega_i = I_f\omega_f.$$

We know I_i, ω_i, and I_f, so we can solve for the final angular velocity ω_f. The answer is $\omega_f = I_i\omega_i/I_f = 3 \times 12/0.5 = 72[\text{rad/s}]$, which corresponds to 11.46 turns per second.

Conservation of Angular Momentum



Kesten & Tauck

<u>Conservation of Angular Momentum</u>

Conservation of Angular Momentum

Conservation of Angular Momentum

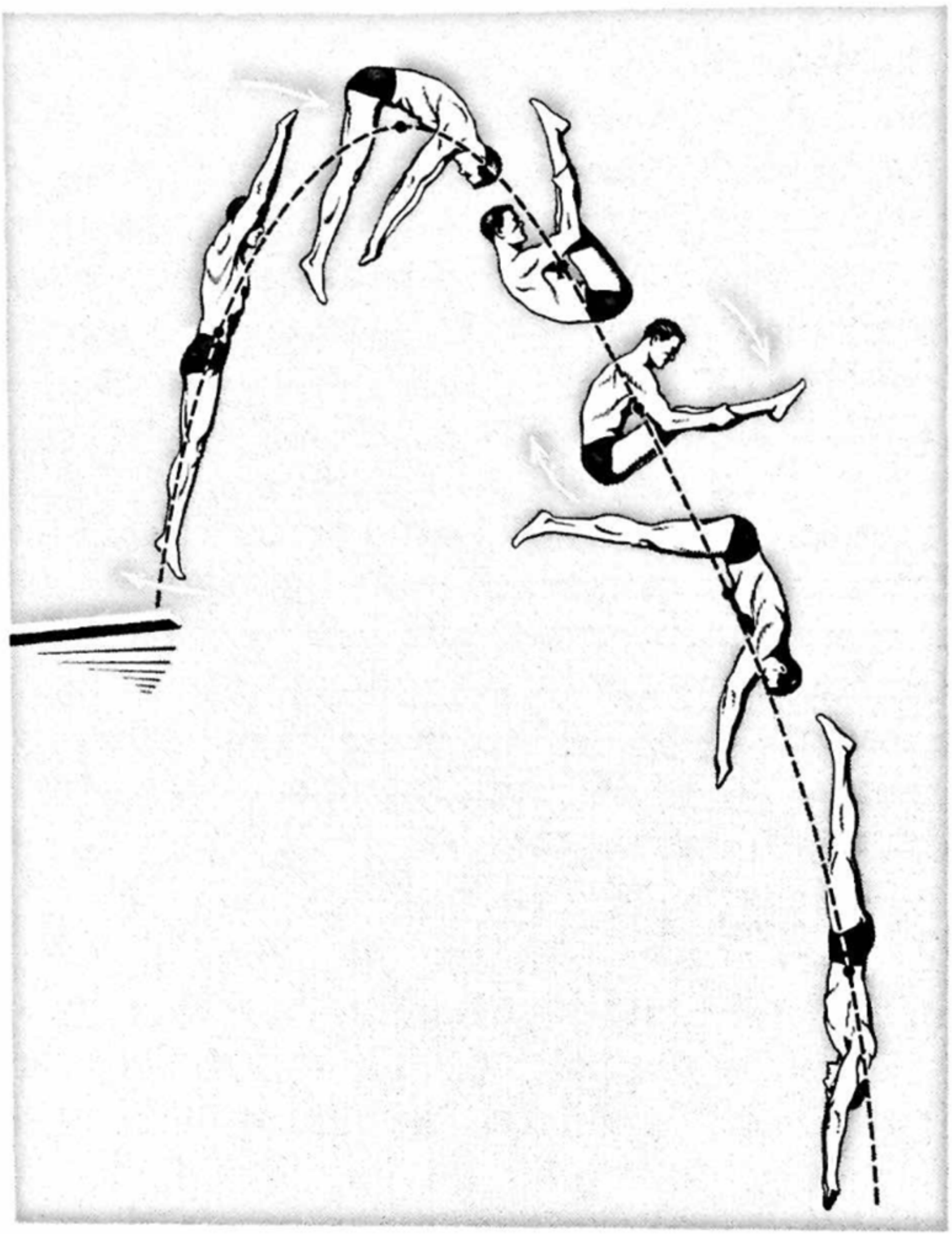


Fig. 13–6 A diver leaves the diving board with arms and legs outstretched and with some initial angular velocity. Since no torques are exerted on him about his center of mass, $L\ (= I\omega)$ is constant while he is in the air. When he pulls his arms and legs in, since I decreases, ω increases. When he again extends his limbs, his angular velocity drops back to its initial value. Notice the parabolic motion of his center of mass, common to all two-dimensional motion under the influence of gravity.

→ There is a bit more here though...

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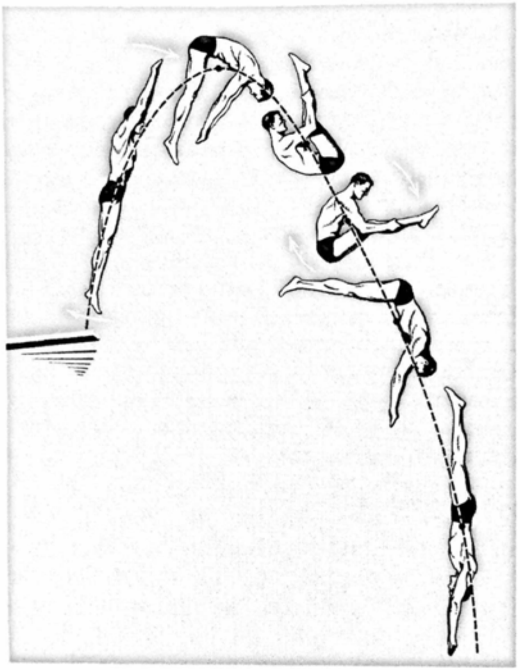
Conservation of Angular Momentum



Note parabolic trajectory of the center-of-mass (CM)

$$I = \sum m_i r_i^2$$

By "tucking in", there is less mass further away re the CM, so therefore I gets smaller

$$I\omega = I_0\omega_0 = \text{a constant.}$$

As a result, ω goes up (and back down as he "extends out" later on)

However, kinetic energy is not constant. Even though the moment of inertia decreases...

$$I < I_0,$$

... it follows that the kinetic energy *increases*!

$$\tfrac{1}{2}I\omega^2 > \tfrac{1}{2}I_0\omega_0^2$$

→ So while momentum is conserved here (i.e., no external torques), the "system" increases in energy by virtue of the diver doing work to extend/pull in body parts to change I

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Spinning Top

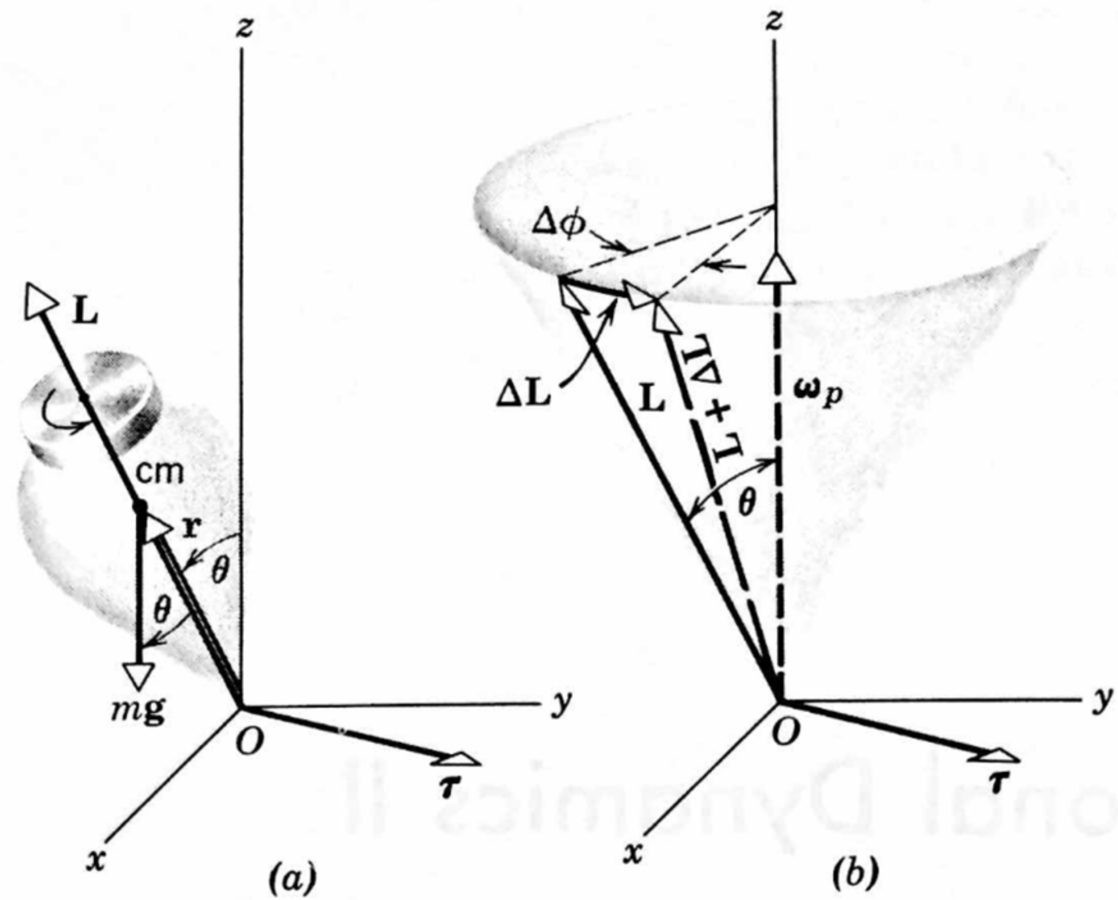

Fig. 13–1 (*a*) A precessing top, showing the angular momentum **L**, the weight $m\mathbf{g}$ and the vector **r** which locates the center of mass. (*b*) The cone swept out by the precessing axis of the top. The angular velocity of precession is shown pointing vertically upward.

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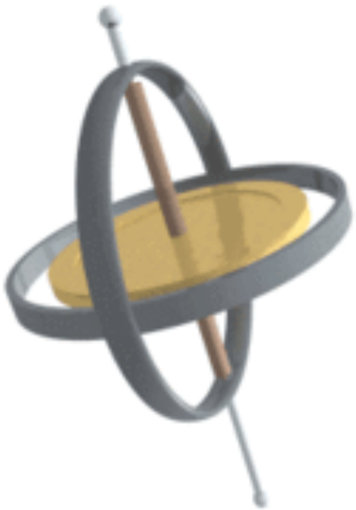
Spinning Top

Spinning top that is precessing

→ Top does not fall over because of its momentum



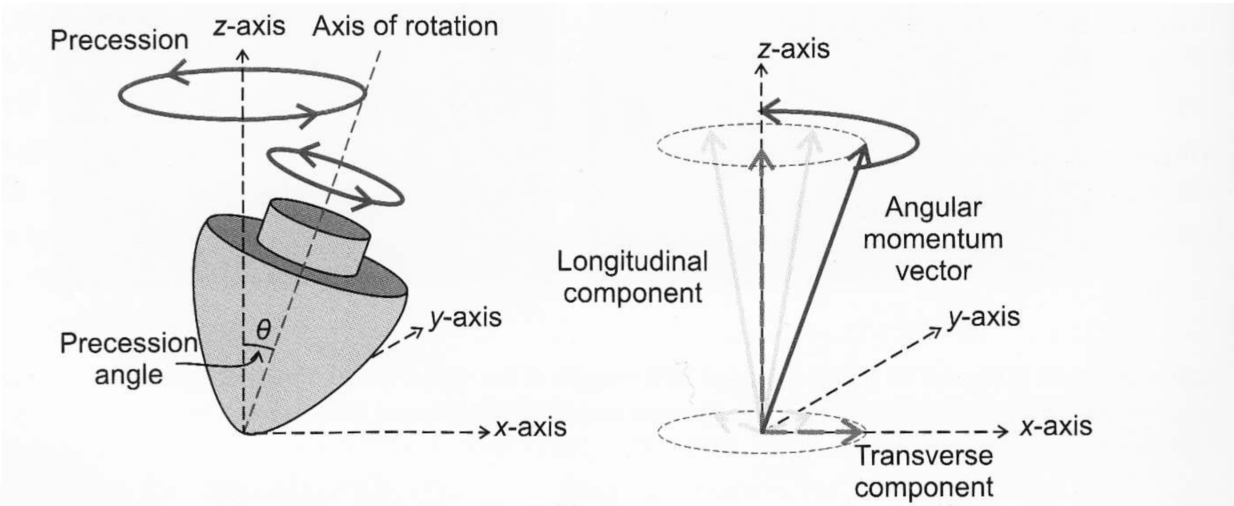


Figure 39.12 The axis of rotation of a spinning top precesses about the vertical. The angular momentum vector of the top has a vertical longitudinal component which is constant and a horizontal transverse component which rotates about the vertical.

→ Note directional conventions **(i.e., longitudinal vs transverse)**

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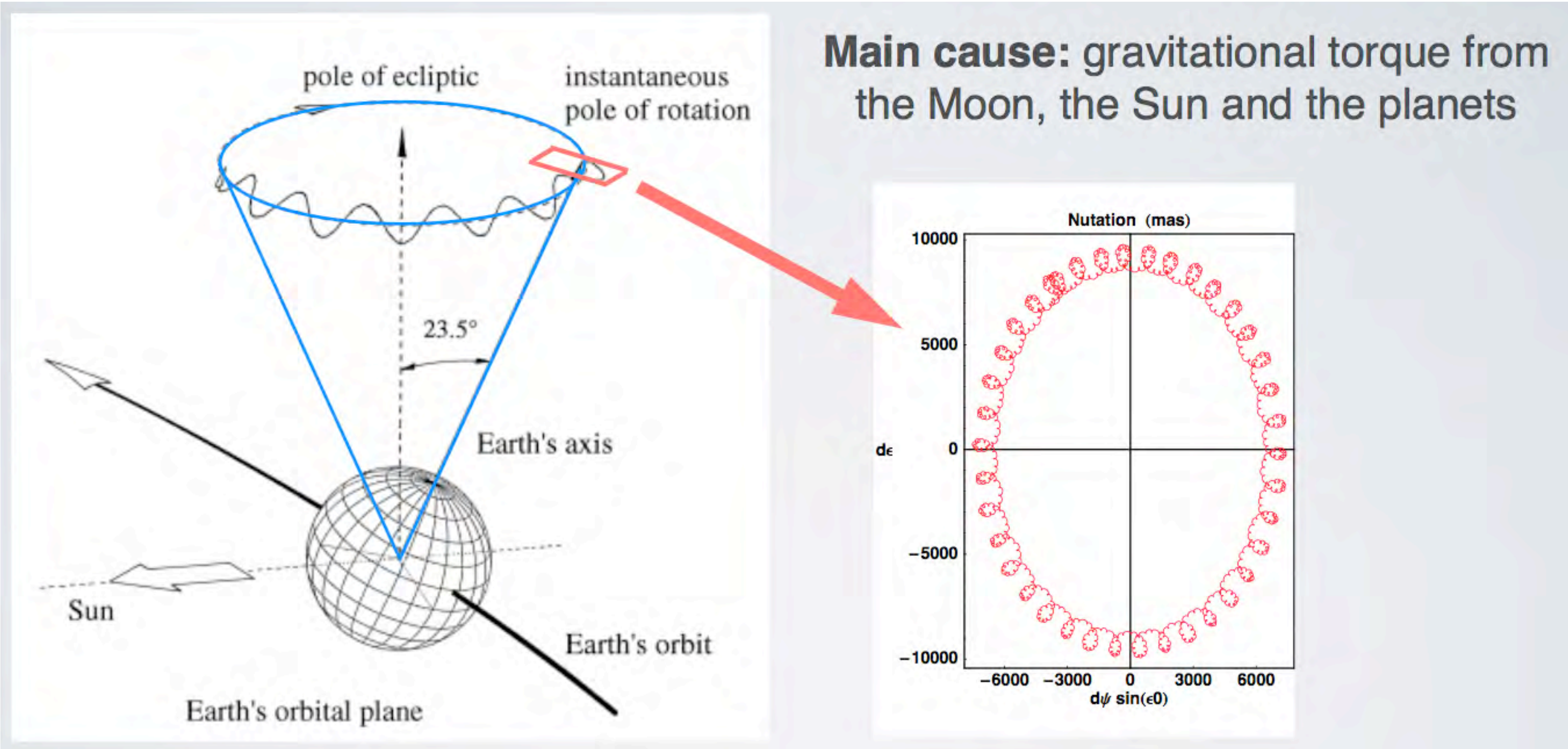
Motions of spinning things…



Earth's motion – Three different rotational axes:
1. Around sun
2. About central axis
3. Nutation of axis

http://www.ualberta.ca/~dumberry/nutation.jpg

<u>Spinning Top</u>

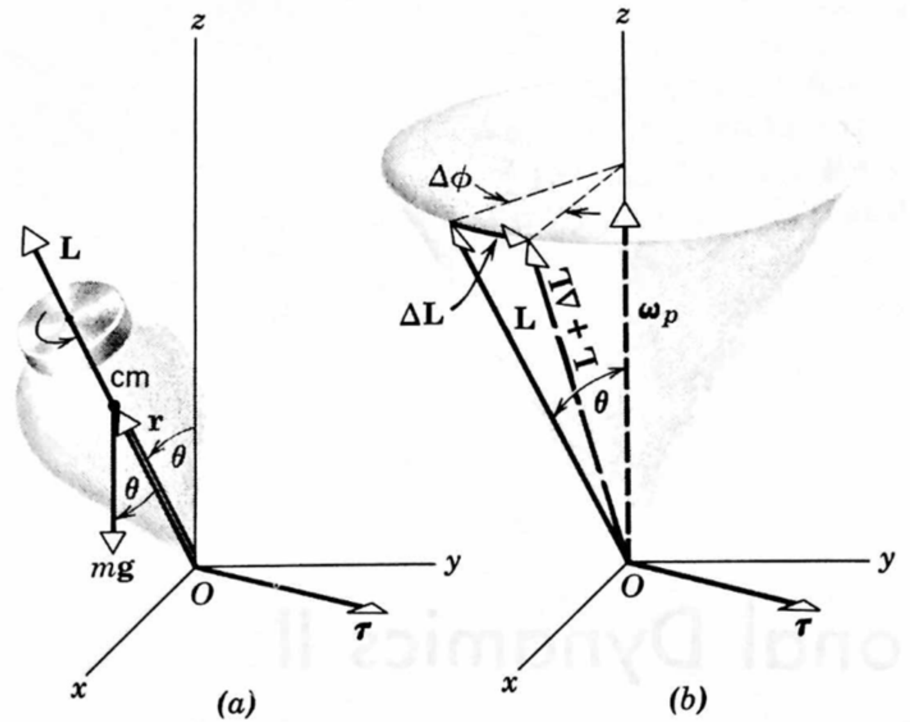


Fig. 13–1 (*a*) A precessing top, showing the angular momentum **L**, the weight $m\mathbf{g}$ and the vector **r** which locates the center of mass. (*b*) The cone swept out by the precessing axis of the top. The angular velocity of precession is shown pointing vertically upward.

We could use the pieces we now have in our toolbox to derive the precession frequency

$$\omega_p = mgr/L.$$

→ Now why mention this here in PHYS 1420?

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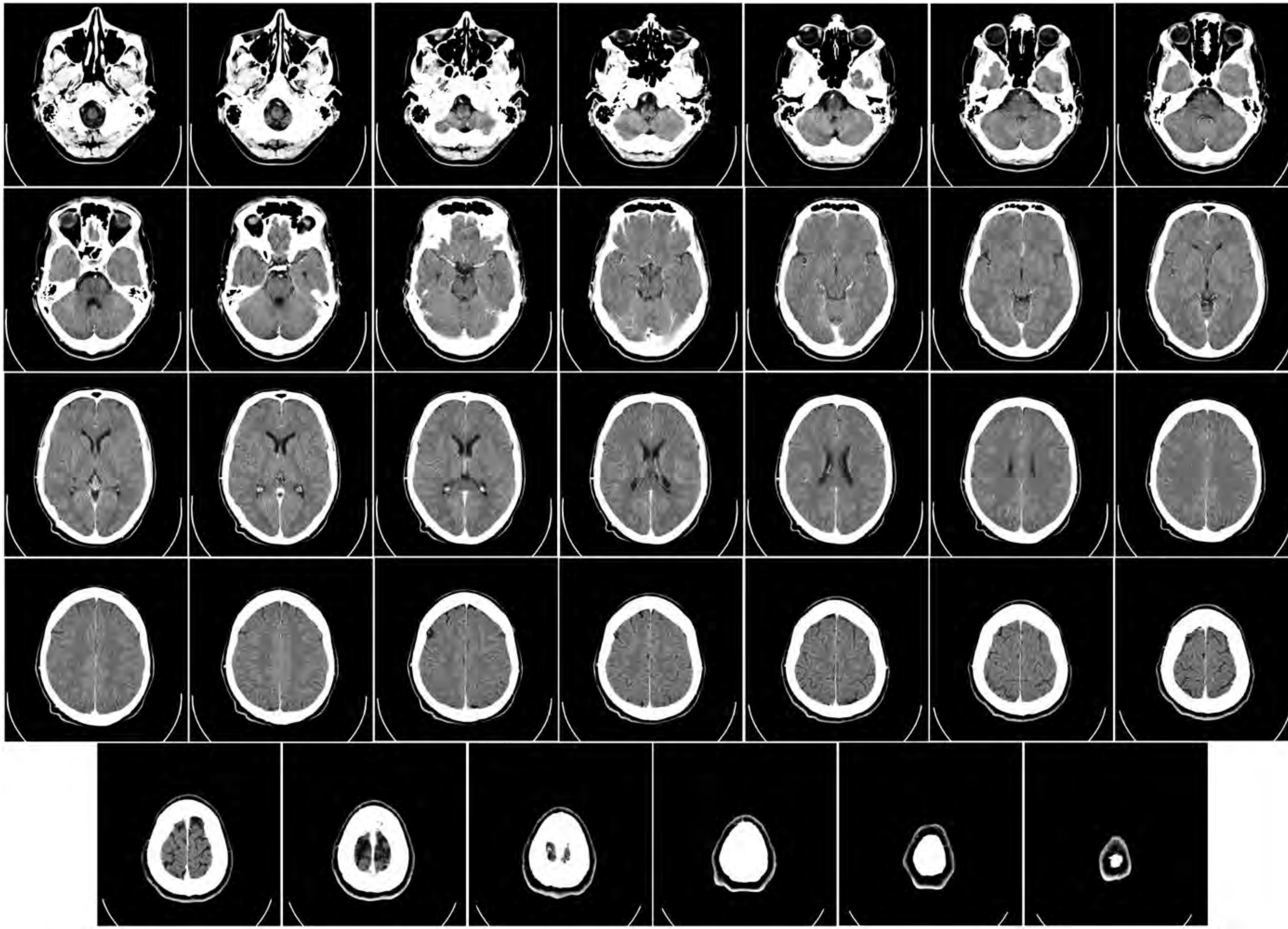
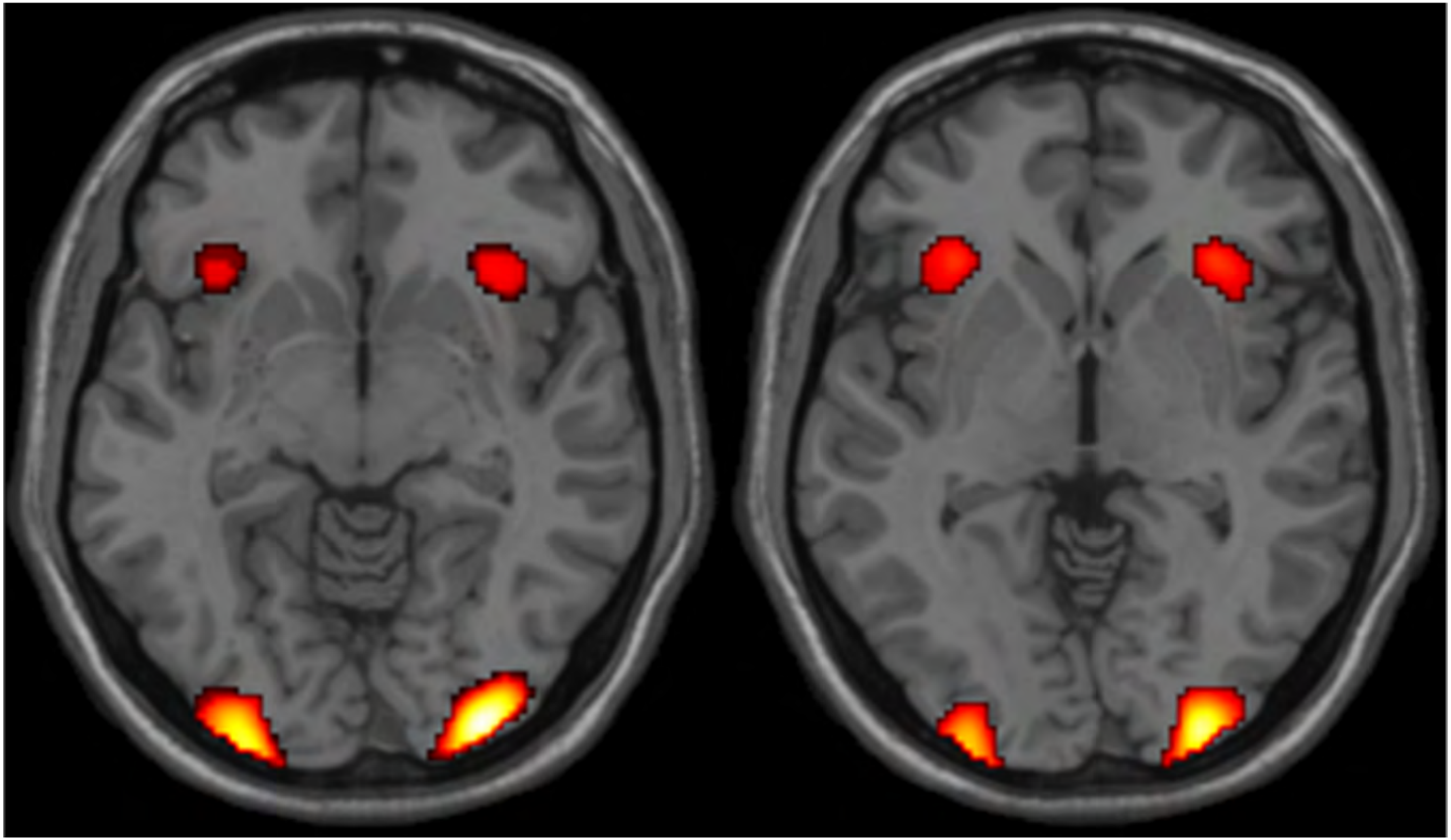


Wikipedia

Wikipedia



http://brainimaging.waisman.wisc.edu/facilities

Universality of conservation of angular momentum

The conservation of angular momentum principle holds in atomic and nuclear physics as well as in celestial and macroscopic regions. Since Newtonian mechanics does not hold in the atomic and nuclear domain, this conservation law must be more fundamental than Newtonian principles.

→ Very deep idea here that connects back to the start of the course...

- What does "physics" even mean?

(from wikipedia)

"**Physics** (from Ancient Greek: φυσική (ἐπιστήμη) *phusikḗ (epistḗmē)* *'knowledge of nature'*, from φύσις *phúsis* "nature)....

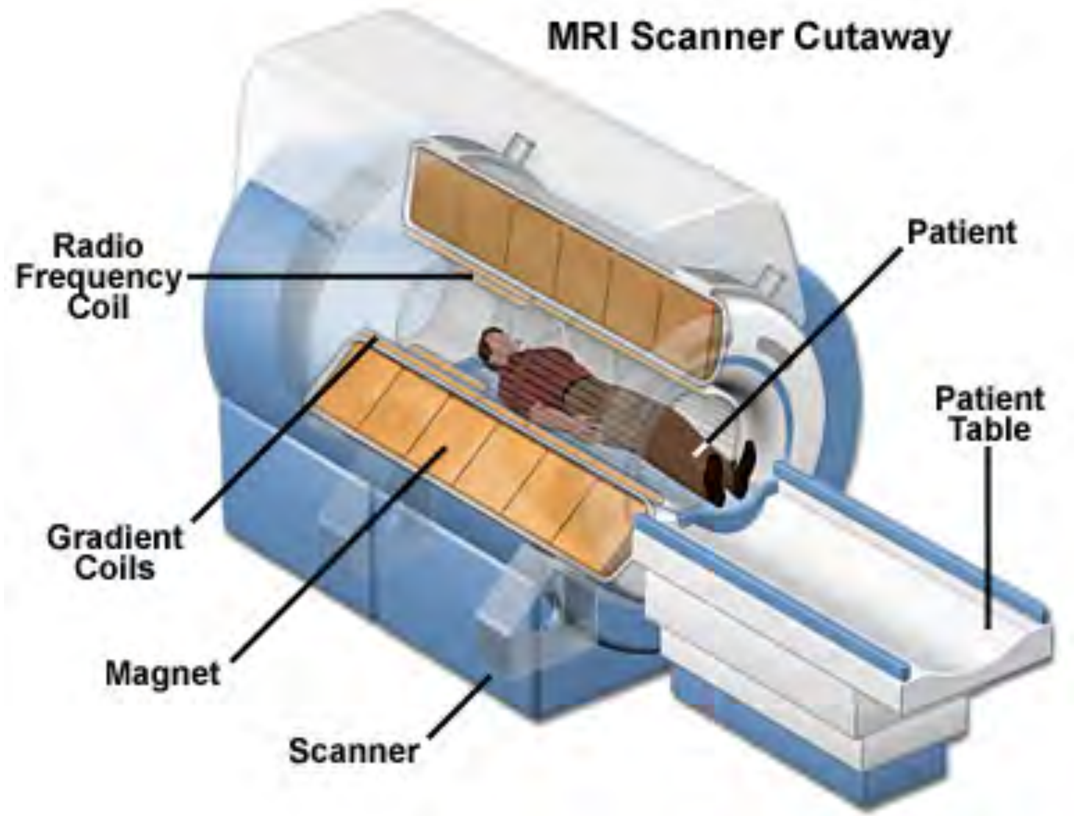
... is the natural science that involves the study of matter and its motion and behavior through space and time, along with related concepts such as energy and force. One of the most fundamental scientific disciplines, the main goal of physics is to understand how the universe behaves."

Resnick & Halliday

<u>NMR/MRI Overview</u>

➢ What are the basic ingredients for NMR/MRI?

- *static field*
- *particles (e.g., protons as spinning tops)*
- *coil to perturb particles from static field and measure resulting dynamics (via 'pulse sequences' of RF photons*)*
- *Fourier transforms*



* RF – Radio Frequency

www.orthopaedics.com

NMR/MRI Overview

→ Let's start with some basics and build up from there......

Note: This will be covered in much more detail in W20 term

- What is magnetism?

phenomena associated with movement of charged particles

- How/why are biological molecules affected by magnetic fields?

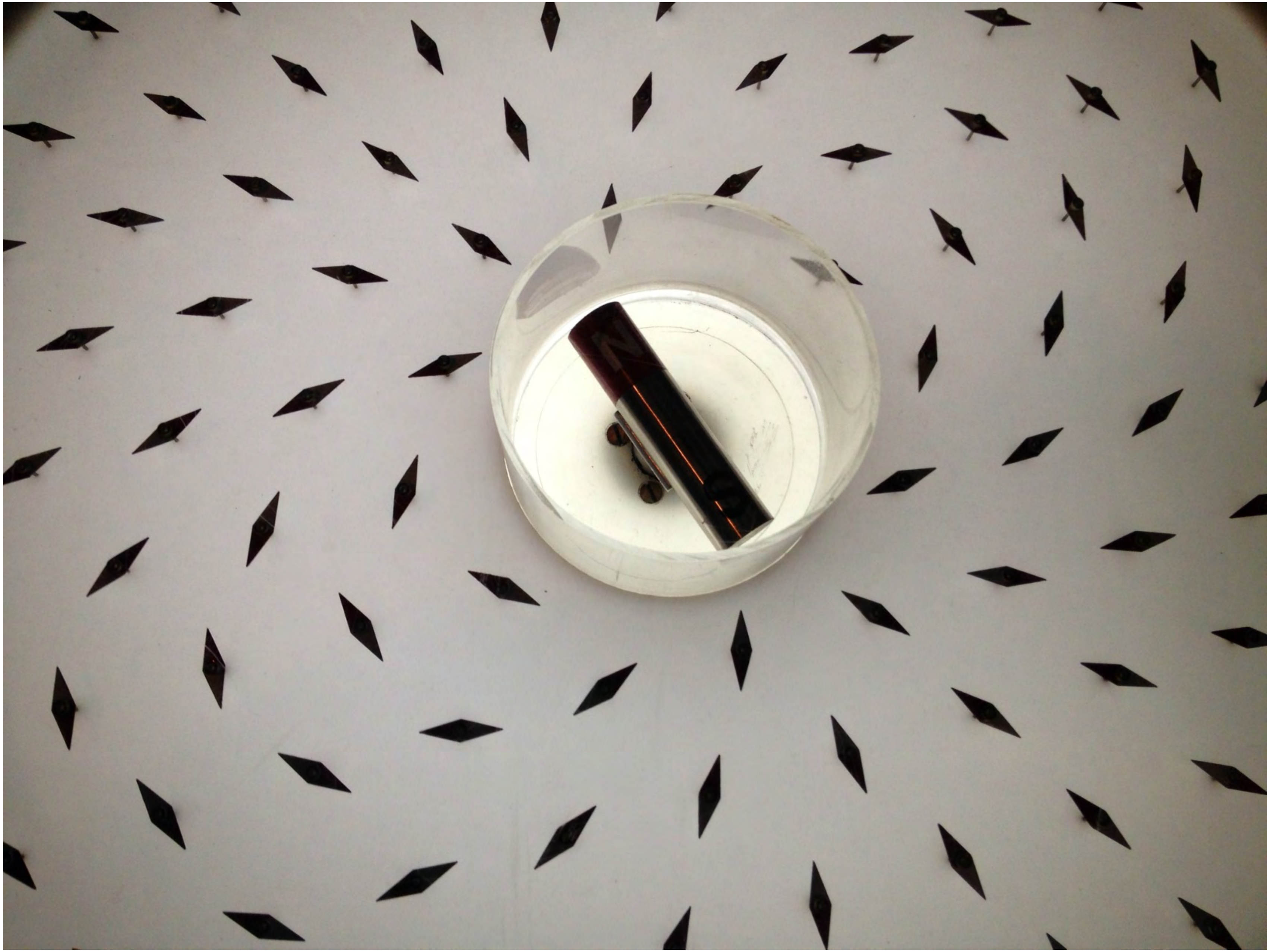
sub-atomic particles have charge and intrinsic angular momentum (i.e., they act as current loops)

- What are the 'units' of magnetism?

  - *B – magnetic filed strength (or flux density)*
  - *$[B]$ = Tesla*
  - *1 T = 10^4 Gauss*
  - *1 Gauss = 10^{-4} kg/C s*
  - *Earth's magnetic field = ~ 0.5 Gauss = 5×10^{-5} T*

- What causes Earth's magnetic field?

currents in Earth's (iron) core; crucially important in protecting us from charged particles incident from space



Ontario Science Centre

NMR/MRI Overview

- What materials are magnetic?

Essentially a quantum effect: how do electrons (with their spin) respond to the external field?

- Is biological tissue 'magnetic'?

Yes, but chiefly due to the protons in the nucleus of H atoms making up water molecules (hence the 'nuclear' part of NMR)

- So why not NMRI?

People generally don't like the word 'nuclear' (i.e., negative connotation)

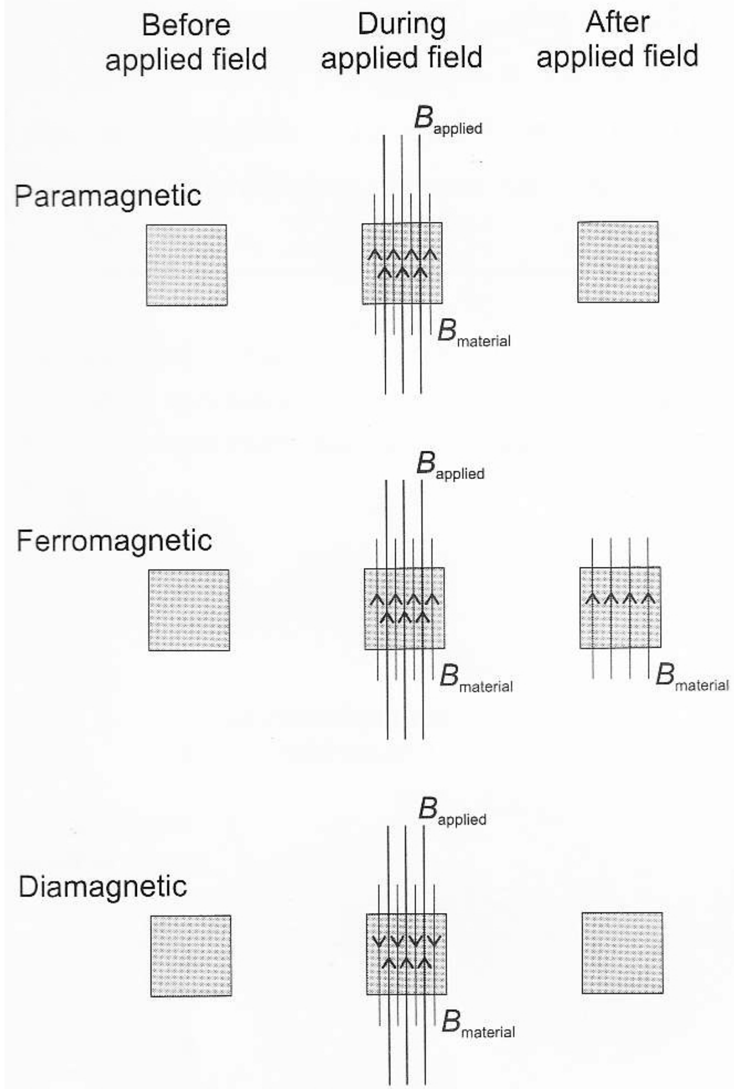


Figure 39.10 Paramagnetism, ferromagnetism, and diamagnetism.

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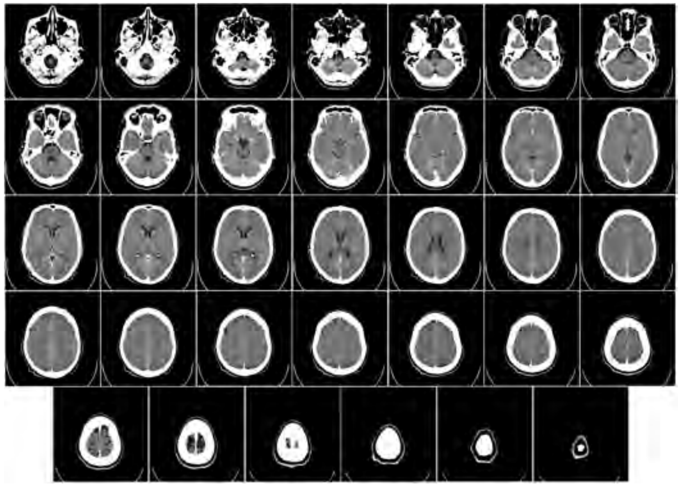
NMR/MRI Overview

- What is the difference between NMR and MRI?

NMR is the physical phenomena that forms the basis of MRI

- How does NMR form an (MRI) image?

→ In a nutshell, the static field aligns sub-atomic particles in the nucleus, which are then stimulated (and subsequently reemit) EM radiation in a spatially-dependent fashion
(the details of this process being our future focus)



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NMR/MRI Overview

Quantum considerations:

- Angular momentum values are quantized (due to possible energy states)
- Only consider hydrogen nucleus (i.e., single proton)
- Can only be in one of two states: 'spin up' or 'spin down'

→ Nuclear angular momentum quantized as quantum number I

$$m = -I, (-I+1) \ldots I$$

$$-\vec{\mu} \cdot \vec{B} = -\gamma \vec{I} \cdot \vec{B} = -\gamma m \hbar \vec{B}$$

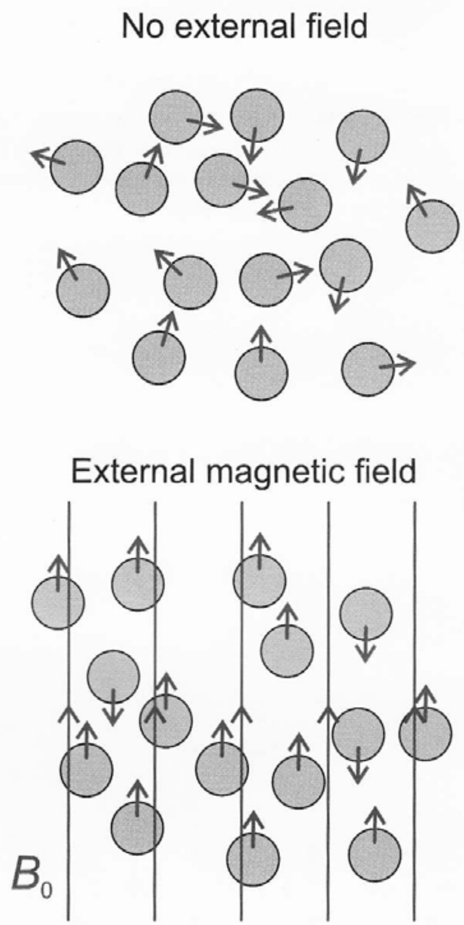


Figure 39.14 In the presence of a static magnetic field, more protons align with the field than against it.

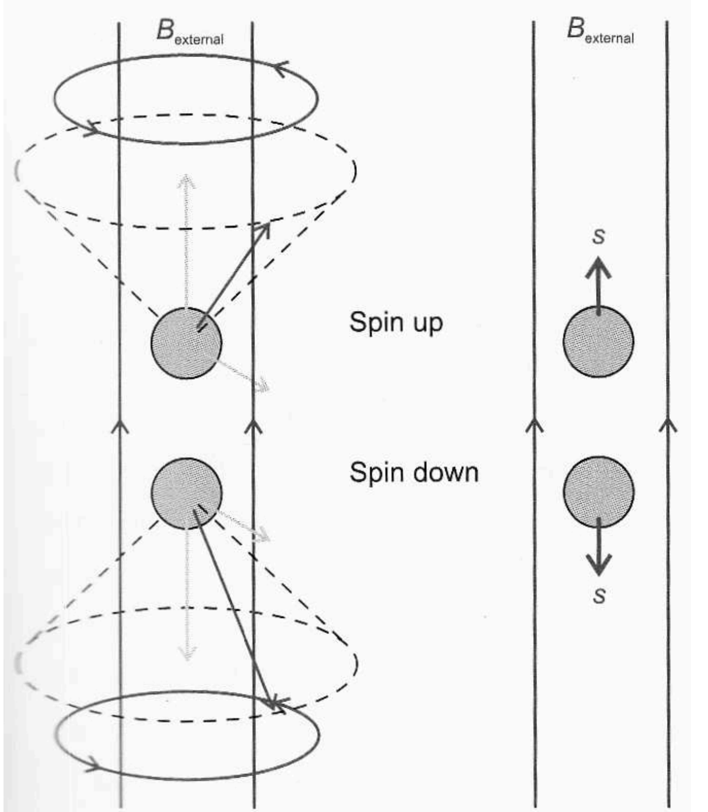
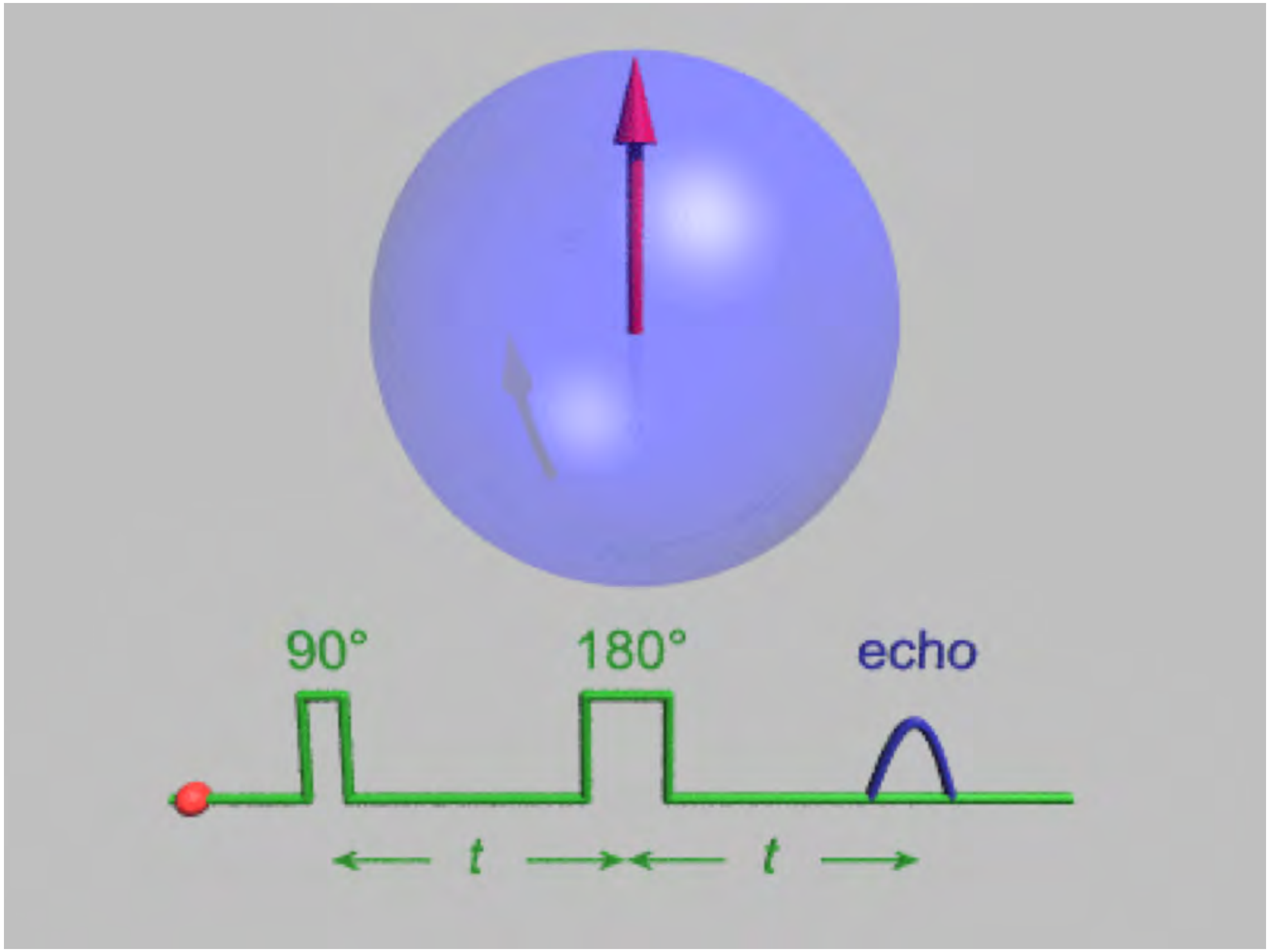


Figure 39.13 The component of the magnetic moment of a proton is measured with respect to an external field. The measured component of the magnetic moment is always a multiple of some fundamental value.

Franklin et al.

Spin Echo Pulse



A. The vertical red arrow is the average magnetic moment of a group of spins, such as protons. All are vertical in the vertical magnetic field and spinning on their long axis, but this illustration is in a rotating reference frame where the spins are stationary on average.

B. A 90 degree pulse has been applied that flips the arrow into the horizontal (x-y) plane.

C. Due to local magnetic field inhomogeneities (variations in the magnetic field at different parts of the sample that are constant in time), as the net moment precesses, some spins slow down due to lower local field strength (and so begin to progressively trail behind) while some speed up due to higher field strength and start getting ahead of the others. This makes the signal decay.

D. A 180 degree pulse is now applied so that the slower spins lead ahead of the main moment and the fast ones trail behind.

E. Progressively, the fast moments catch up with the main moment and the slow moments drift back toward the main moment.

F. Complete refocusing has occurred and at this time, an accurate T_2 echo can be measured with all T_2^* effects removed. Quite separately, return of the red arrow towards the vertical (not shown) would reflect the T_1 relaxation. 180 degrees is π radians so 180° pulses are often called π pulses.

Wikipedia (spin echo)

NMR/MRI Overview

➢ What is the difference between T1 and T2 imaging?

Protons are excited by RF pulse and relax back towards an equilibrium (thereby re-emitting RF photons) in two ways: longitudinal (along static field; T1) and transverse (perpendicular to static field; T2)

Differences are due to how protons lose energy: T1 due to proton's surrounding environment (spin-lattice) and T2 due interactions amongst protons (spin-spin)

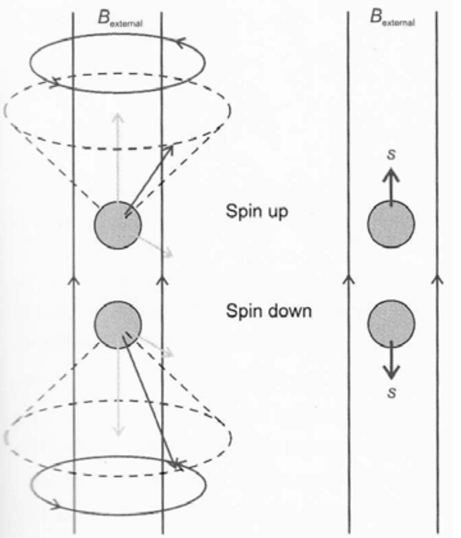


Figure 39.13 The component of the magnetic moment of a proton is measured with respect to an external field. The measured component of the magnetic moment is always a multiple of some fundamental value.

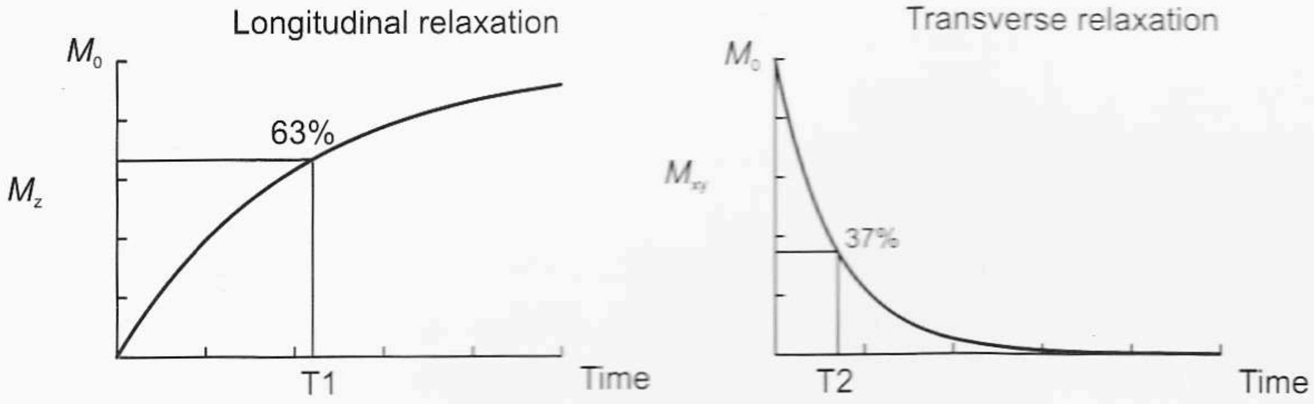


Figure 39.17 The longitudinal and transverse components of the bulk magnetisation return to their original values following a resonant RF pulse.

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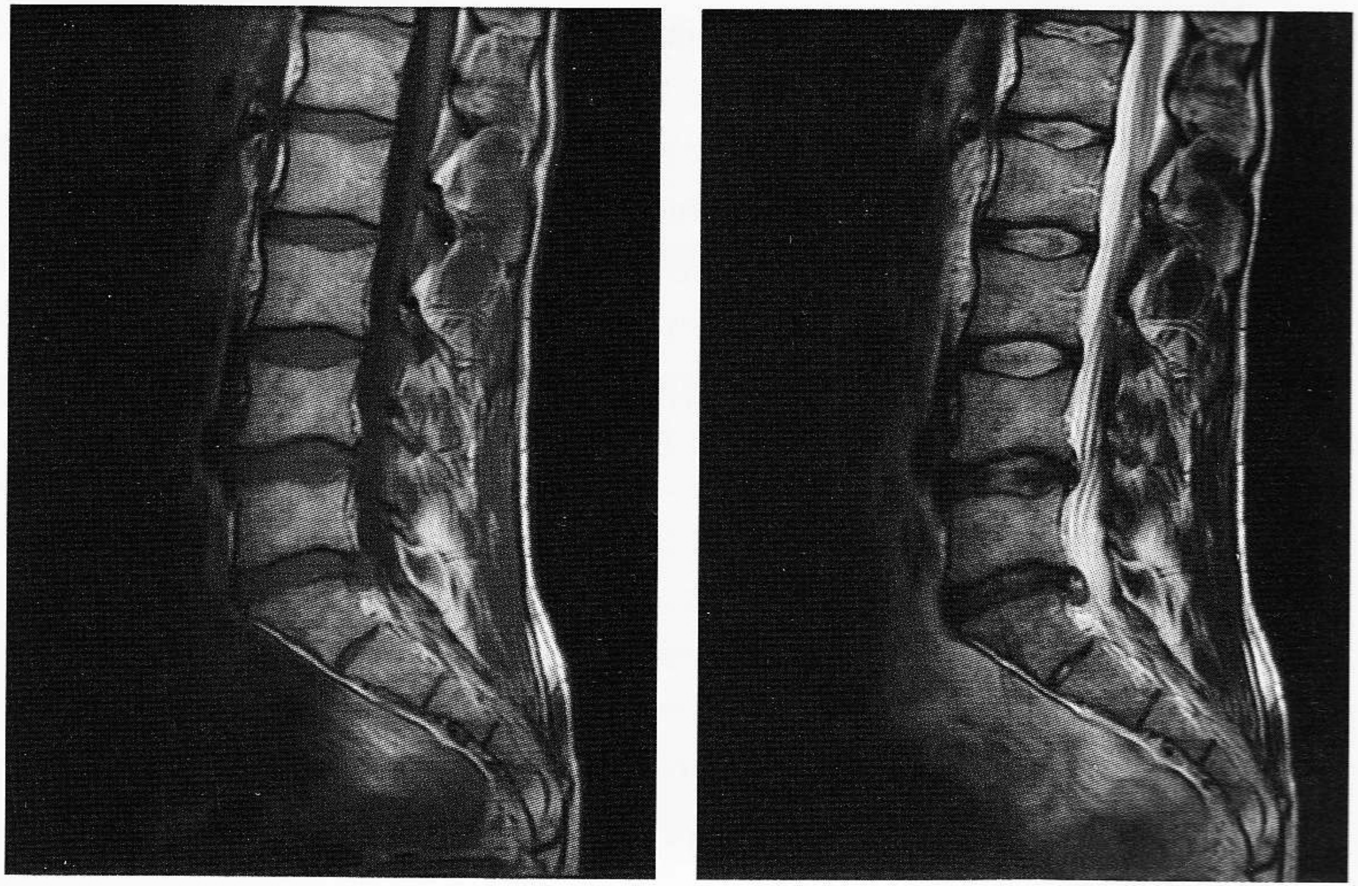

Figure 39.11 T1 (left) and T2 (right) weighted MRI images of the same spine. These images show a lumbosacral intervertebral disc protrusion (slipped disc). [Images courtesy of Professor Terry Doyle, University of Otago School of Medicine.]

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<u>NMR/MRI Overview</u>

- How is MRI used for medical imaging?

Wide variety of different imaging modalities allow for radiologists to image tissue both in terms of structure (e.g., tumor present?anomaly in shape?) and/or physiology (e.g., high region of blood uptake?)

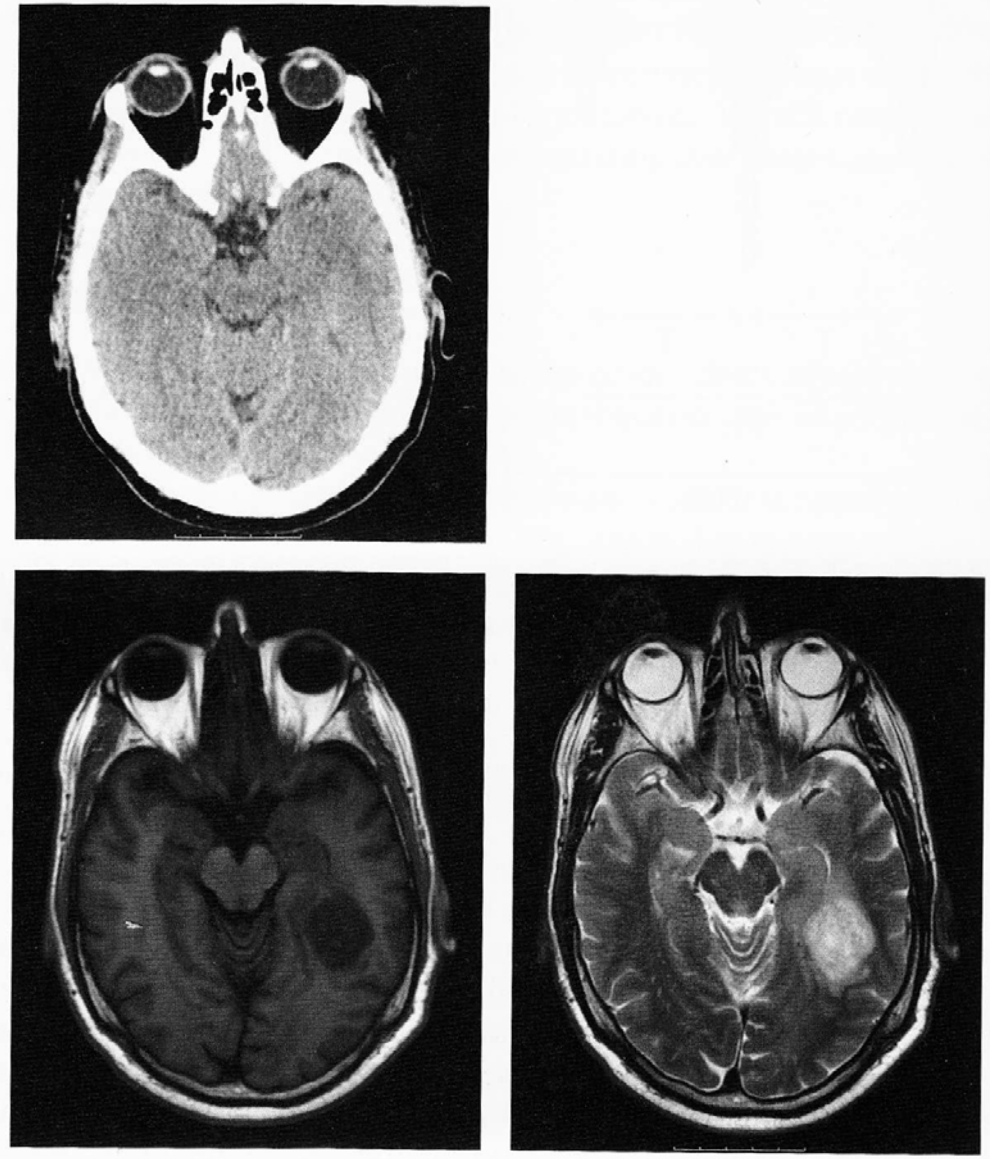
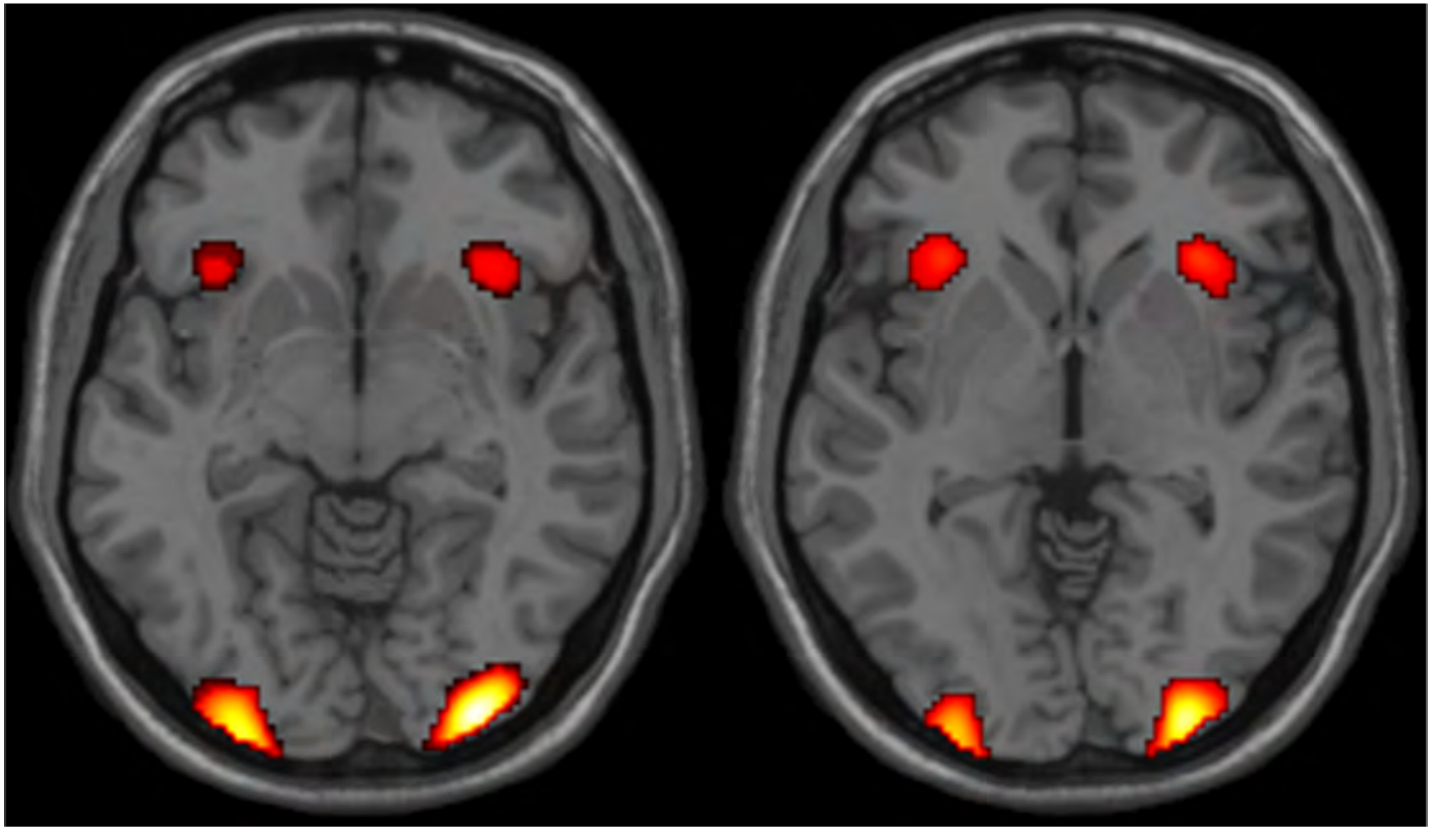


Figure 39.21 (Top) A CT scan of a patient's head. The patient had an unexplained accident but the CT scan showed no abnormality. (Bottom left) T1-weighted MRI image of the same patient located in the same place as the CT image. This image shows a low contrast image of a tumour in the left temporal lobe. (Bottom right) A T2-weighted image in which the large water signal in the tumour is clear. [Images courtesy of Professor Terry Doyle, University of Otago School of Medicine.]

Franklin et al.

- What is fMRI?

The ‘f’ stands for functional and allows for dynamics to be observed (via the BOLD signal, or Blood Oxygenation Level Dependence); very popular technique in the field of ‘neuroimaging’



Universality of conservation of angular momentum

Further reading:

The conservation of angular momentum principle holds in atomic and nuclear physics as well as in celestial and macroscopic regions. Since Newtonian mechanics does not hold in the atomic and nuclear domain, this conservation law must be more fundamental than Newtonian principles. In our derivation of this principle we must have made more rigid assumptions than we needed to. This is true even in the framework of classical mechanics. The student should note the key role played by Newton's third law in our deduction of this conservation principle. This law was used to justify the assumption that the sum of the internal torques was zero. It was necessary to assert not only that the action and reaction forces were equal and opposite (the "weak" form of the third law) but also that these forces were directed along the line joining the two particles (the "strong" form of the third law). The strong form is known to be violated in some electromagnetic interactions. However, the assumption that the sum of the internal torques in a system of particles is zero can be proven on the basis of a much less stringent requirement than that the third law should hold.*

The law of conservation of angular momentum, as we have formulated it, holds for a system of bodies whenever the bodies can be treated as particles, that is, whenever effects due to the rotation of the individual bodies can be neglected. When the individual bodies have rotation, the conservation of angular momentum principle is still valid, providing we include the angular momentum associated with this rotation. However, the bodies then are no longer simple particles whose motion can be described by particle dynamics.

Resnick & Halliday

Universality of conservation of angular momentum

Further reading:

In atomic and nuclear physics we find that the "elementary particles" such as electrons, protons, mesons, and neutrons have angular momentum associated with an intrinsic spinning motion, as well as with orbital motion about some external point. When we use the law of conservation of total angular momentum we must include this *spin* angular momentum in the total. A fundamental aspect of atomic, molecular, and nuclear systems is that their angular momenta can take on only definite discrete values, rather than a continuum of values. Angular momentum is said to be *quantized*. Hence, angular momentum plays a central role in the description of the behavior of such systems (see Problems 4 and 6). These ideas will be developed in later chapters.

If we were to regard the sun, planets, and satellites as particles having no intrinsic spinning motion, the angular momentum of the solar system would turn out not to be constant. But these bodies do have intrinsic rotations; in fact, tidal forces convert some of the intrinsic spinning angular momentum into orbital angular momentum of the planets and satellites. When we use the law of conservation of the angular momentum, we must include this spin angular momentum in the total. The conservation of angular momentum plays a key role in the evaluation of theories of the origin of the solar system, the contraction of giant

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* See E. Gerjuoy, *American Journal of Physics*, Vol. 17, 477 (1949).

Resnick & Halliday

Universality of conservation of angular momentum

Further reading:

stars, and other problems in astronomy.* Some astronomical applications will be considered in Chapter 16.

The basis for this rather simple way of analyzing the total angular momentum of atomic or astronomical systems is a theorem (see Problem 10) that the *total* angular momentum **L** of any system with respect to the origin of an inertial reference frame may be computed by adding the angular momentum with respect to its center of mass (*spin* angular momentum) to the angular momentum arising from the motion of the center of mass with respect to the origin (*orbital* angular momentum).

The conservation laws of total energy and of linear momentum and angular momentum are fundamental to physics, being valid in all modern physical theories. We shall have occasion to use them many times in later chapters.

Resnick & Halliday

NMR/MRI Overview

“How would you explain NMR to someone without a scientific background?”

“First, NMR allows you to determine the structure and connectivity of molecules or even to image the human body. NMR works by probing the responses of atomic nuclei in a magnetic field. These nuclei act like spies who give you coded messages that you record with electronic equipment. Once you’ve recorded these messages, you can try to analyze and understand them.”

“The nuclei have a magnetic moment, which means they react to an applied magnetic field. When you apply an external magnetic field the nuclei start to precess, or change the orientation of their rotational axis, with a frequency that is proportional to the field strength.”

Q&A Richard R. Ernst

A man of many dimensions

A pioneer of one- and two-dimensional nuclear magnetic resonance (NMR), Ernst talks to Stephanie Harris about why dimensions are important in life as well as in science.

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The nuclei have a magnetic moment, which means they react to an applied magnetic field. When you apply an external magnetic field the nuclei start to precess, or change the orientation of their rotational axis, with a frequency that is proportional to the field strength. If you measure the precessional frequency you can determine the local magnetic field, which differs from the applied magnetic field because of shielding from the electrons that surround the nuclei. The difference between the two fields provides important information about the chemical environment around the nuclei within the molecule — whether it is electron-rich or -poor.

NMR can also tell us about the structure of a molecule: how the nuclei are spatially arranged. This is because the magnetic moments of nearby nuclei perturb the local magnetic field of the nucleus under study, introducing fine structure or splitting of the observed resonance. The precise nature of this splitting — whether it is split into two, three, four or a more complex pattern — tells us how many nuclei surround the one of interest. And the spacing of the lines in the pattern allows us to determine the distance between the nuclei.

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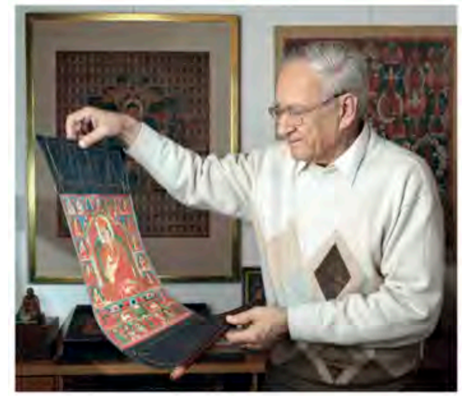

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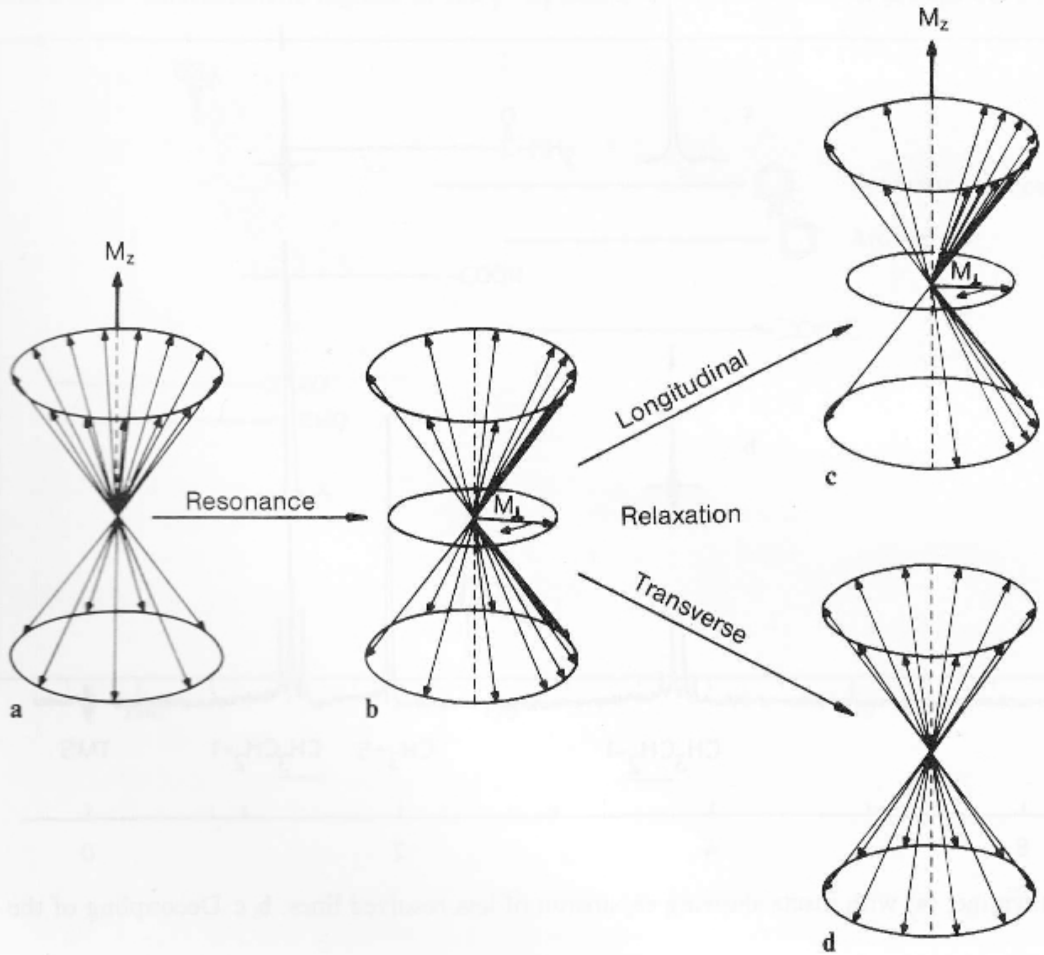

Fig. 3.147a–d. Classical representation of the NMR experiment. **a** In equilibrium the nuclear spins are distributed in the states α and β according to the Boltzmann distribution. **b** At resonance, and with a sufficiently strong RF field, the populations of α and β are equalized and the spins precess in phase at the Larmor frequency ω_L. **c** Longitudinal relaxation restores the equilibrium distribution of the spins. **d** The phase coherence of the spins is lost by transverse relaxation. In reality the processes **c** and **d** proceed simultaneously