Dynamics of Potentials and Force Fields
(Ch. 7 and part of Ch. 8 of Unit 1)

Potential energy dynamics of Superballs and related things

Thales geometry and “Sagittal approximation” to superball force law
Geometry and dynamics of single ball bounce
(a) Constant force $F=-k$ (linear potential $V=kx$)
   Some physics of dare-devil diving 80 ft. into kidee pool
(b) Linear force $F=-kx$ (quadratic potential $V=\frac{1}{2}kx^2$ (like balloon))
(c) Non-linear force (like superball-floor or ball-bearing-anvil)

Geometry and potential dynamics of 2-ball bounce
A parable of RumpCo. vs CrapCorp. (introducing 3-mass potential-driven dynamics)
A story of USC pre-meds visiting Whammo Manufacturing Co.

Geometry and dynamics of n-ball bounces
Analogy with shockwave and acoustical horn amplifier
   Advantages of a geometric $m_1, m_2, m_3,...$ series
   A story of Stirling Colgate (Palmolive) and core-collapse supernovae

Many-body 1D collisions
   Elastic examples: Western buckboard
      Bouncing columns and Newton’s cradle
   Inelastic examples: “Zig-zag geometry” of freeway crashes
   Super-elastic examples: This really is “Rocket-Science”
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- Elastic examples: Western buckboard
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What is superball bounce force law $F(x)$?

$F(x) = \ ?$

$\frac{x}{r} = \frac{r}{2R-x}$

Thales' geometry and "Sagittal\#" approx.

$r = \sqrt{x(2R-x)} \quad (\approx \sqrt{2Rx} \text{ for } x << R)$

\#"bow"
If superball was a balloon its bounce force law would be linear $F = -k \cdot x$ (Hooke Law)

$$F_{\text{balloon}}(x) = P \cdot A = P \cdot \pi r^2$$

$$\approx P \cdot \pi 2Rx$$
If superball was a balloon its bounce force law would be linear $F = -k \cdot x$ (Hooke Law)

$F_{\text{balloon}}(x) = P \cdot A = P \cdot \pi r^2$

$\approx P \cdot \pi 2Rx = P \cdot 2\pi Rx$ (Hooke spring constant $k$)

$= kx$
Potential Energy Geometry of Superballs and Related things

What is superball bounce force law $F(x)$?

If superball was a balloon its bounce force law would be linear $F = -k \cdot x$ (Hooke Law)

$F_{\text{balloon}}(x) = P \cdot A = P \cdot \pi r^2 \\ \approx P \cdot \pi 2Rx = P \cdot 2\pi Rx$ (Hooke spring constant $k$)

Instead superball force law depends on bulk volume modulus and is non-linear $F \sim x^p$? +? (Power Law?)

Volume($X$) = $\int_0^X \pi r^2 \, dx = \int_0^X \pi x(2R - x) \, dx$
Potential Energy Geometry of Superballs and Related things

If superball was a balloon its bounce force law would be linear $F = -k \cdot x$ (Hooke Law)

$F_{\text{balloon}}(x) = P \cdot A = P \cdot \pi r^2$

$\approx P \cdot \pi 2Rx = P \cdot 2\pi Rx$

$= kx$

Instead superball force law depends on bulk volume modulus and is non-linear $F \sim x^p$? +? (Power Law?)

$Volume(X) = \int_0^X \pi r^2 \, dx = \int_0^X \pi x(2R-x) \, dx = \int_0^X 2R\pi x \, dx - \int_0^X \pi x^2 \, dx = R\pi X^2 - \frac{\pi X^3}{3} \approx \begin{cases} R\pi X^2 & (\text{for } X << R) \\ \frac{4}{3} \pi R^3 & (\text{for } X = 2R) \end{cases}$
Potential Energy Geometry of Superballs and Related things

What is superball bounce force law $F(x)$?

If superball was a balloon its bounce force law would be linear $F = -k \cdot x$ (Hooke Law)

$F_{balloon}(x) = P \cdot A = P \cdot \pi r^2$

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It also depends on velocity $\dot{x} = \frac{dx}{dt}$. Adiabatic differs from Isothermal as shown by “Project-Ball”*


(Discussed after p. 33)
Potential energy dynamics of Superballs and related things

Thales geometry and “Sagittal approximation” to force law

Geometry and dynamics of single ball bounce

General Non-linear force (like superball-floor or ball-bearing-anvil)

Constant force $F = -k$ (linear potential $V = kx$)

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Many-body 1D collisions

Elastic examples: Western buckboard

Bouncing columns and Newton’s cradle

Inelastic examples: “Zig-zag geometry” of freeway crashes

Super-elastic examples: This really is “Rocket-Science”
(a) **Drop height**  
(Zero kinetic energy)  
- Force is weight $mg$ only  
- Height $h$

(b) **Maximum kinetic energy**  
(Zero total force)  
- Floor force balances weight $mg$  
- Force is zero

(c) **Maximum penetration**  
(Zero kinetic energy again)  
- Force is maximum

Details of each case follows using newer Web simulations

1990 BounceIt Mac simulations

**BounceIt Simulation: Force/Potential Plot**
BounceIt Simulation: Force/Potential Plot

Sets gravity

This is linear setting (increase for non-linear)
(a) Drop height $h$
(Zero kinetic energy)

Total potential energy curve $U(x) + mg Y$

Total energy $E = mgh$

Display of Force vector using similar triangle construction based on the slope of potential curve.
Floor force balances weight $mg$.

In equilibrium,

$$x_{static}$$

Force is zero.

Kinetic energy $KE$ = Total energy $E$

$$F(x) + mg$$

Total potential energy curve $U(x) + mgY$

$(b)$ Maximum kinetic energy

(Zero total force)
(c) Maximum penetration
(Zero kinetic energy again)

Display of Force vector using similar triangle construction based on the slope of potential curve.
(a) Drop height \( h \)  
(Zero kinetic energy)

(b) Maximum kinetic energy  
(Zero total force)

(c) Maximum penetration  
(Zero kinetic energy again)

**Display of Force vector using similar triangle construction based on the slope of potential curve.**
Potential energy dynamics of Superballs and related things

Thales geometry and “Sagittal approximation” to force law
Geometry and dynamics of single ball bounce

General Non-linear force (like superball-floor or ball-bearing-anvil)
Constant force $F = -k$ (linear potential $V = kx$)

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Force $F(x)$ and Potential $U(x)$ for soft heavy non-linear superball

Unit 1
Fig. 7.5

Total Energy $E = Mg y$

$U_{total}(y) = -Mgx + U_{ball}(y)$

$F_{total}(y) = -Mg + F_{ball}(y)$

$F(x) = -\frac{dU(x)}{dx}$

$U_{total}(y) = \int_{y_{static}}^{y_{max}} F_{total}(y) \, dy + \int_{y_{static}}^{y_{max}} F_{total}(y) \, dy + U(h) = U(h) = E$
**Force** $F(x)$ and **Potential** $U(x)$ for soft heavy non-linear superball

**Total Energy** $E=Mgh$

$$F_{\text{total}}(y) = -Mg + F_{\text{ball}}(y)$$

$$U_{\text{total}}(y) = -Mgx + U_{\text{ball}}(y)$$

$$W = \int F(x) \, dx = \text{Energy acquired} = \text{Area of } F(x) = -U(x)$$

$$F(x) = -\frac{dU(x)}{dx}$$
Force $F(x)$ and Potential $U(x)$ for soft heavy non-linear superball

Total Energy $E = Mgh$

$$U_{total}(y) = -Mgx + U^{ball}(y)$$

$$F_{total}(y) = -Mg + F^{ball}(y)$$

$y_{max}$

$y_{static}$

$y = h$

$$U_{total}(y_{max}) = \int_{y_{static}}^{y_{max}} F_{total}(y) \, dy + \int_{y = h}^{y_{static}} F_{total}(y) \, dy + U(h) = U(h) = E$$

Work $W = \int F(x) \, dx = \text{Energy acquired} = \text{Area of } F(x) = -U(x)$

$$F(x) = -\frac{dU(x)}{dx}$$

Impulse $P = \int F(t) \, dt = \text{Momentum acquired} = \text{Area of } F(t) = P(t)$

$$F(t) = \frac{dP(t)}{dt}$$
Potential energy dynamics of Superballs and related things

- Thales geometry and “Sagittal approximation” to force law
- Geometry and dynamics of single ball bounce
  - General Non-linear force (like superball-floor or ball-bearing-anvil)
    - Constant force $F = -k$ (linear potential $V = kx$)
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    - Linear force $F = -kx$ (quadratic potential $V = \frac{1}{2}kx^2$ (like balloon))

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- A parable of RumpCo. vs CrapCorp. (introducing 3-mass potential-driven dynamics)
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Geometry and dynamics of $n$-ball bounces

- Analogy with shockwave and acoustical horn amplifier
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- A story of Stirling Colgate (Palmolive) and core-collapse supernovae

Many-body 1D collisions

- Elastic examples: Western buckboard
  - Bouncing columns and Newton’s cradle
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- Super-elastic examples: This really is “Rocket-Science”
Main Control Panel

Sets gravity

This is linear setting (increase for non-linear)
Figure 7.3

(a) Constant Force Linear Potential Models:

\[ F(x) = k \]

\[ U(x) = -kx \]

(b) Potential \( U(x) \) (Units of \( \text{MgY Joules} \))

(c) (Force=6) \times (Distance=5)

(d) (Force=-1) \times (Distance=30)

\[ F(x) = \frac{dU(x)}{dx} \]

\[ F(t) = \frac{dP(t)}{dt} \]

\[ \text{Work} = W = \int F(x) \, dx = \text{Energy acquired} = \text{Area of } F(x) = -U(x) \]

\[ \text{Impulse} = P = \int F(t) \, dt = \text{Momentum acquired} = \text{Area of } F(t) = P(t) \]

\[ \int_{-1 \text{ m}}^{30 \text{ m}} (\text{Force}=30) \times (\text{Distance}=1) \]

\[ \int_{-1 \text{ m}}^{30 \text{ m}} (\text{Force}=-1) \times (\text{Distance}=30) \]

\[ \text{Area}=+30 \]

\[ \text{Area}=-30 \]

\[ \text{Gentle Force} \]

\[ \text{Strong Force} \]

\[ \text{Medium Force} \]

\[ \text{Potential jump} = -30 \]
Potential energy dynamics of Superballs and related things
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Super-elastic examples: This really is “Rocket-Science”
**Unit 1**

Fig. 7.4

**Potential Energy** and **Force** for a Soft and Hard ball

- **Soft Ball**
  - Force: $F = -k_s x$
  - Potential: $U = \frac{1}{2} k_s x^2$

- **Hard Ball**
  - Force: $F = -k_H x$
  - Potential: $U = mg(y + \frac{1}{2}ky^2)$

**Note**: dashed curve followed by PE minimum. Parabola? What?

**Additional Information**

- **Force $F$**
  - $F = -k y$
  - $F = -k y^2$

- **Potential $U$**
  - $U = \frac{1}{2} k y^2$
  - $U = mg(y + \frac{1}{2}ky^2)$

- **Graphs**
  - Unit 1
  - Force vs. Y-distance
  - Potential vs. Y-distance

**Mathematical Equations**

- $F_{Total} = F_{grav} + F_{target} = \begin{cases} -Mg & (y \geq 0) \\ -Mg - ky & (y < 0) \end{cases}$

- $U_{Total} = U_{grav} + U_{target} = \begin{cases} Mg y & (y \geq 0) \\ Mg y + \frac{1}{2} ky^2 & (y < 0) \end{cases}$
Potential energy dynamics of Superballs and related things

Thales geometry and “Sagittal approximation” to force law
Geometry and dynamics of single ball bounce

General Non-linear force (like superball-floor or ball-bearing-anvil)
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Geometry and dynamics of n-ball bounces

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$U_{\text{total}}(y) = -Mgx + U_{\text{ball}}(y)$

$W = W = \int F(x) \, dx = \text{Energy acquired} = \text{Area of } F(x) = -U(x)$

$P = \int F(t) \, dt = \text{Momentum acquired} = \text{Area of } F(t) = P(t)$

Total Energy $E = Mg \gamma$
Potential energy dynamics of Superballs and related things

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Geometry and potential dynamics of 2-ball bounce

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Parable allegory for Los Alamos
Cheap & practical “seat-of-the pants” approach

Parable allegory for Livermore
Fancy & overpriced “political” approach

Advantages of a geometric $m_1, m_2, m_3, ...$ series

A story of Stirling Colgate (Palmolive) and core-collapse supernovae

Many-body 1D collisions

Elastic examples: Western buckboard

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Parable allegory for Los Alamos
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Unit 1
Fig. 7.6
Parable allegory for Los Alamos
Cheap & practical “seat-of-the pants” approach

Parable allegory for Livermore
Fancy & overpriced “political” approach

RumpCo
Project Ball
2-Bang Model

Crap Corp
Star Wars Division
Super Elastic Bounce
Full Force Field Simulation

Velocity amplification
or “throw” factor = 2.5

Unit 1
Fig. 7.6

Velocity amplification
or “throw” factor = 2.3

(about equal to RumpCo
finite gap experiment)
Cooperation between Los Alamos and Livermore yields insight to answer “What’s going on?”

Quite surprising “non-effect”! Why?
Cooperation between Los Alamos and Livermore yields insight to answer “What’s going on?”

Velocity amplification or “throw” factor = 1.03 (practically “no-throw”) for linear force $F(y) = ky$.

Flat part of non-linear force gives “explosive” effect.

Linear Force $F(y) = y^1$

Quadratic $F(y) = y^2$

Quartic $F(y) = y^4$

Velocity 1

Velocity 2

$V_2 = 1.03$

$V_1 = 0.996$

Continuous Bounce Sequence

Unit 1

Fig. 7.7
Potential energy dynamics of Superballs and related things
    Thales geometry and “Sagittal approximation” to force law
    Geometry and dynamics of single ball bounce
        (a) Constant force $F=-k$ (linear potential $V=kx$)
            Some physics of dare-devil-diving 80 ft. into kidee pool
        (b) Linear force $F=-kx$ (quadratic potential $V=\frac{1}{2}kx^2$ (like balloon))
        (c) Non-linear force (like superball-floor or ball-bearing-anvil)

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Velocity Amplification in Collision Experiments ...and some results of “Project-Ball” Involving Superballs

INTRODUCTION

Shortly after the well-known Superball\(^1\) appeared on the market, one of the authors quite accidentally discovered a surprising effect.\(^2\) The point of a ball point pen is imbedded in the surface of a 3-in. diam Superball, and the pen and ball are dropped from a height of 4 or 5 ft so that the pen remains above the ball and perpendicular to a hard floor below. As the ball strikes the floor, the pen may be ejected so violently that it will strike the ceiling of the average room with considerable force. Furthermore, one can adjust the mass of the pen so that the ball remains completely at rest on the floor after ejection of the pen.

\(^{1}\) Trade name of product by Whammo Manufacturing Co., San Gabriel, Calif.

\(^{2}\) Much later…

Lots of profs try this out... ...

...including the unfortunate Harvard professor M. Tinkham...

( Still trying to find the video of the Tinkham incident...)

Basketball and Tennis Ball

Dropping a tennis ball on top of a basketball causes the tennis ball to bounce very high.

Source: 8.01 Physics I: Classical Mechanics, Fall 1999
Prof. Walter Lewin

Course Material Related to This Topic:

- Watch video clip from Lecture 17 (21:30 - 24:08)

A story of USC pre-meds visiting Whammo Manufacturing Co.

...and some results of “Project-Ball”

After initial big NBC splash (Ray Dunkin Reports) in Fall 1968, USC mechanical engineers kindly measured super-ball force curves $F(y)$ with their precision tensometer and let us use their analog computer to calculate precise bounce heights.
A story of USC pre-meds visiting Whammo Manufacturing Co.

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After this things began deteriorating in Old-Physics-Rm 69 (The Project-Ball-Room)

1. The fancy-pants computer theory did not jive with the fine drop-tower experiments.
2. USC B&G decided Rm 69 needed painting and kicked us out for a week.
A story of USC pre-meds visiting Whammo Manufacturing Co.  
...and some results of “Project-Ball”

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A call to Whammo Co. elicited interest in a big $$$$ product. Invited us to visit. Yay! $$$

Little paint spots on floor show what was wrong with our fancy-pants computer theory

After initial big NBC splash (Ray Dunkin Reports) in Fall 1968, USC mechanical engineers kindly measured super-ball force curves F(y) with their precision tensometer and let us use their analog computer to calculate precise bounce heights.
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Days later, finally, got a car convoy together so we all could visit San Gabriel plant.
A story of USC pre-meds visiting Whammo Manufacturing Co.

...and some results of “Project-Ball”

After initial big NBC splash (Ray Dunkin Reports) in Fall 1968, USC mechanical engineers kindly measured super-ball force curves $F(y)$ with their precision tensometer and let us use their analog computer to calculate precise bounce heights.

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But, that was “Alpha-Wave” day for inventors at San Gabriel plant.
So we end up talking to Whammo lawyer/owner.
A story of USC pre-meds visiting Whammo Manufacturing Co.

...and some results of “Project-Ball”

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So we end up talking to Whammo lawyer/owner:

He says invention too dangerous. Bummmer! No$$! (Forget Feynman’s suggestion of Ceiling Dartboard.)
Seeing us looking sad he offers us boxes of super-balls of many sizes (and other shapes).
A story of USC pre-meds visiting Whammo Manufacturing Co.

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A call to Whammo Co. elicited interest in a big $$ product. Invited us to visit. Yay! $$

Days later, finally, got a car convoy together so we all could visit San Gabriel plant.

But, that was “Alpha-Wave” day for inventors at San Gabriel plant.
So we end up talking to Whammo lawyer/owner:

He says invention too dangerous. Bummer! No$$! (Forget Feynman's suggestion of Ceiling Dartboard.)
Seeing us looking sad he offers us boxes of super-balls of many sizes (and other shapes).

Still a little sad, we return to Rm 69.
Somebody drops a box of balls that immediately bounce into the wet paint.
A story of USC pre-meds visiting Whammo Manufacturing Co.

...and some results of “Project-Ball”

After initial big NBC splash (Ray Dunkin Reports) in Fall 1968, USC mechanical engineers kindly measured super-ball force curves $F(y)$ with their precision tensometer and let us use their analog computer to calculate precise bounce heights.

After this things began deteriorating in Old-Physics-Rm 69 (The Project-Ball-Room)

1. The fancy-pants computer theory did not jive with the fine drop-tower experiments.
2. USC B&G decided Rm 69 needed painting and kicked us out for a week.

A call to Whammo Co. elicited interest in a big $$$ product. Invited us to visit. Yay! $$$

Days later, finally, got a car convoy together so we all could visit San Gabriel plant.

But, that was “Alpha-Wave” day for inventors at San Gabriel plant.
So we end up talking to Whammo lawyer/owner:

He says invention too dangerous. Bummer! No$$! (Forget Feynman’s suggestion of Ceiling Dartboard.)
Seeing us looking sad he offers us boxes of super-balls of many sizes (and other shapes).

Still a little sad, we return to Rm 69.
Somebody drops a box of balls that immediately bounce into the wet paint.

The rest is history.
Little paint spots on floor show what was wrong with our fancy-pants computer theory
A story of USC pre-meds visiting Whammo Manufacturing Co.

...and some results of “Project-Ball”

The rest is history.
Little paint spots on floor show what was wrong with our fancy-pants computer theory.

The engineering curves were isothermal not adiabatic.
Need latter. Can do latter by dropping dyed balls and measuring spot-size.

Measuring spot-size $d$ gives energy vs. height.
Slope of $E(x)$ gives force $F(x)$ and $G(x)$.  

Fro. 10. Sagittal formula.

Collisions Involving Superballs
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Slope of $E(x)$ gives force $F(x)$ and $G(x)$.

If $F(x)$ and $G(x)$ were linear for all $x$, then the

Then fancy-pants computer theory can predict N-ball tower bounce
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**Fig. 10.** Sagittal formula.

If \(F(x)\) and \(G(x)\) were linear for all \(x\), then the

**Fig. 12.** Adiabatic force function \(G(x)\).

**Functions** \(F(x)\) and \(G(x)\) were then placed on the function generators of the analog computer.

Then fancy-pants computer theory can predict \(N\)-ball tower bounce

**Fig. 11.** Adiabatic force \(F(x)\) and energy curves for Superball.

**Fig. 13.** Comparison between analog computer gain curves and second experiment.
Then fancy-pants computer theory can predict N-ball tower bounces.

Fig. 11. Adiabatic force $F(x)$ and energy curves for Superball.

Fig. 13. Comparison between analog computer gain curves and experiment.

Here are some 3-ball tower bounce predictions

Class of W. G. Harter

Fig. 14. Two designs for a multiple stage tower of balls. (a) Large number of balls can slide on a shaft. (b) Balls connected by small pins stand to lose appreciable amounts of binding energy.

Fig. 15. (a)–(d) Analog computer output for velocity gains of three-ball system.

Functions $F(x)$ and $G(x)$ were then placed on the function generators of the analog computer.
Potential energy dynamics of Superballs and related things
Thales geometry and “Sagittal approximation” to force law
Geometry and dynamics of single ball bounce
   (a) Constant force $F=-k$ (linear potential $V=lx$)
   Some physics of dare-devil-diving 80 ft. into kiddee pool
   (b) Linear force $F=-kx$ (quadratic potential $V=\frac{1}{2}kx^2$ (like balloon))
   (c) Non-linear force (like superball-floor or ball-bearing-anvil)

Geometry and potential dynamics of 2-ball bounce
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Advantages of a geometric $m_1, m_2, m_3, ...$ series
A story of Stirling Colgate (Palmolive) and core-collapse supernovae

Many-body 1D collisions
Elastic examples: Western buckboard
   Bouncing columns and Newton’s cradle
Inelastic examples: “Zig-zag geometry” of freeway crashes
Super-elastic examples: This really is “Rocket-Science”
Unit 1
Fig. 8.1a-c
Independent Bang Model
(IBM)
3-Body Geometry

BounceIt Simulation: 3-Ball Tower w/ Quartic Force

BounceIt Simulation: 3-Ball Tower w/ Linear Force
Unit 1
Fig. 8.1b
Independent Bang Model (IBM)
3-Body Geometry

(a) Quartic Force
\[ F(y) = ky^4 \]
- \( m_3 = 10 \text{ kg} \)
- \( m_2 = 30 \text{ kg} \)
- \( m_1 = 100 \text{ kg} \)

Initial Velocities
- \( V_3 = -1 \text{ m/s} \)
- \( V_2 = -1 \text{ m/s} \)
- \( V_1 = -1 \text{ m/s} \)

Final Velocities
- \( V_3 = 3.41 \text{ m/s} \)
- \( V_2 = 0.701 \text{ m/s} \)
- \( V_1 = 0.298 \text{ m/s} \)

(b) Independent Collisions (Independent of Force Law)

Initial Velocities
- \( V_3 = -1 \text{ m/s} \)
- \( V_2 = -1 \text{ m/s} \)
- \( V_1 = -1 \text{ m/s} \)

Final Velocities
- \( V_3 = 3.52 \text{ m/s} \)
- \( V_2 = 0.538 \text{ m/s} \)
- \( V_1 = 0.077 \text{ m/s} \)

(c) Linear Force
\[ F(y) = ky \]
- \( m_3 = 18 \text{ kg} \)
- \( m_2 = 30 \text{ kg} \)
- \( m_1 = 100 \text{ kg} \)

Initial Velocities
- \( V_3 = -1 \text{ m/s} \)
- \( V_2 = -1 \text{ m/s} \)
- \( V_1 = -1 \text{ m/s} \)

Final Velocities
- \( V_3 = 1.48 \text{ m/s} \)
- \( V_2 = 1.32 \text{ m/s} \)
- \( V_1 = 0.81 \text{ m/s} \)
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Many-body 1D collisions

Elastic examples: Western buckboard

Bouncing columns and Newton’s cradle

Inelastic examples: “Zig-zag geometry” of freeway crashes

Super-elastic examples: This really is “Rocket-Science”
1.8.3 The optimal idler (An algebra/calculus problem)
To get highest final $v_3$ of mass $m_3$ find optimum mass $m_2$ in terms of masses $m_1$ and $m_3$ that does that.
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Source
http://hubblesite.org/newscenter/archive/releases/2007/10/image/a/

Author
NASA, ESA, P. Challis, and R. Kirshner (Harvard-Smithsonian Center for Astrophysics)

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<table>
<thead>
<tr>
<th>Process</th>
<th>Main fuel</th>
<th>Main products</th>
<th>Temperature (Kelvin)</th>
<th>Density (g/cm³)</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>hydrogen burning</td>
<td>hydrogen</td>
<td>helium</td>
<td>7×10⁷</td>
<td>10</td>
<td>10⁷ years</td>
</tr>
<tr>
<td>triple-alpha process</td>
<td>helium</td>
<td>carbon, oxygen</td>
<td>2×10⁸</td>
<td>2000</td>
<td>10⁶ years</td>
</tr>
<tr>
<td>carbon burning process</td>
<td>carbon</td>
<td>Ne, Na, Mg, Al</td>
<td>8×10⁸</td>
<td>10⁶</td>
<td>10³ years</td>
</tr>
<tr>
<td>neon burning process</td>
<td>neon</td>
<td>O, Mg</td>
<td>1.6×10⁹</td>
<td>10⁷</td>
<td>3 years</td>
</tr>
<tr>
<td>oxygen burning process</td>
<td>oxygen</td>
<td>Si, S, Ar, Ca</td>
<td>1.8×10⁹</td>
<td>10⁷</td>
<td>0.3 years</td>
</tr>
<tr>
<td>silicon burning process</td>
<td>silicon</td>
<td>nickel (decays into iron)</td>
<td>2.5×10⁹</td>
<td>10⁸</td>
<td>5 days</td>
</tr>
</tbody>
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http://hubblesite.org/newscenter/archive/releases/2007/10/image/a/

NASA, ESA, P. Challis, and R. Kirshner (Harvard-Smithsonian Center for Astrophysics)

Core-burning nuclear fusion stages for a 25-solar mass star

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<tr>
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<td>neon</td>
<td>O, Mg</td>
<td>1.6 \times 10^9</td>
<td>10^7</td>
<td>3 years</td>
</tr>
<tr>
<td>oxygen burning process</td>
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</table>

Within a massive, evolved star (a) the onion-layered shells of elements undergo fusion, forming a nickel-iron core (b) that reaches Chandrasekhar mass and starts to collapse. The inner part of the core is compressed into neutrons (c), causing infalling material to bounce (d) and form an outward-propagating shock front (red). The shock starts to stall (e), but it is reinvigorated by neutrino interaction. The surrounding material is blasted away (f), leaving only a degenerate remnant.
Stirling Auhincios Colgate (November 14, 1925 – December 1, 2013) was an American physicist at Los Alamos National Laboratory and a professor emeritus of physics, past president at the New Mexico Institute of Mining and Technology (New Mexico Tech),[1] and an heir to the Colgate toothpaste family fortune.[2] He was America's premier diagnostician of thermonuclear weapons during the early years at the Lawrence Livermore National Laboratory in California. While much of his involvement with physics is still highly classified, he made many contributions in the open literature including physics education and astrophysics.[3] He was born in New York City in 1925, to Henry Auhincios and Jeanette Thurber (née Pruyn) Colgate.[4]

..an amusing off-color aside story of Stirling Colgate’s NMIMT resignation...

(Not told in Wikipedia!)

Quote

- "I was always enamored with explosives, and eventually I graduated to dynamite and then nuclear bombs."
Multiple-collision accelerator assembly
US 5256071 A

ABSTRACT
A device comprising several highly elastic objects is presented whose purpose is to demonstrate an unobvious consequence of fundamental laws of physics—the acceleration of an object to high speed by multiple collisions among a series of heavier objects moving at slower speed. The objects, each of different mass, are arrayed in close proximity in order of decreasing mass with their centers lying along a straight line. This arrangement of the assembly of objects is maintained by a constraining element which permits the assembly axis to be oriented in any desired direction and permits the assembly to be moved or manipulated as a unit in any desired way without destroying the arrangement of objects. In the preferred embodiment the elastic objects are polybutadiene balls (12), the constraining element is an interior guide-pin (10) fastened in the largest ball and extending radially therefrom, on which the remaining balls can slide freely because of diametrical holes formed in them. In use this multiple-collision accelerator assembly is suspended in vertical orientation, with the largest ball downward, by holding the tip-end of the guide-pin which extends beyond the littlest ball. The assembly is then dropped onto a solid surface (14), the striking of which produces a sharp impulse that is transmitted from the largest ball, through the assembly, causing the littlest ball to be projected to a height many times that from which the assembly was dropped.

1st publication describing theory and experiment of this device 20 years before.

(Point allowing patent over previous 1973 proposal (4))

Velocity Amplification in Collision Experiments Involving Superballs
William G. Harter\(^1\) (class of WGH)

---
HIDE AFFILIATIONS
\(^1\) University of Southern California, Los Angeles, California 90007

View the Scitation page for University of Southern California (USC).

Am. J. Phys. 39, 656 (1971); http://dx.doi.org/10.1119/1.1986253

(Now I have to pay APS for my own paper.)
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Many-body 1D collisions
Elastic examples: Western buckboard
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Inelastic examples: “Zig-zag geometry” of freeway crashes
Super-elastic examples: This really is “Rocket-Science”
Western buckboard = ?????
Western buckboard = ?????
Western buckboard = 3-ball analogy
Western buckboard  = 3-ball analogy Disaster!
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Unit 1
Fig. 8.2a-b
4-Body IBM Geometry
Fig. 8.2c-d
4-Equal-Body Geometry

Bouncelt Simulation: 4-Ball Tower w/ \( m_k/m_{k+1} = 3 \)

Bouncelt Simulation: 4-Ball Tower w/ \( m_k/m_{k+1} = 1 \)

4-Equal-Body
“Shockwave” or pulse wave Dynamics

Opposite of continuous wave dynamics introduced in Unit 2
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Super-elastic examples: This really is “Rocket-Science”
Inelastic examples: “Zig-zag geometry” of freeway crashes
First recall “zig-zag” fractions of “Monster Mash” in Lect. 4

Trajectory geometry exposed (Harmonic series 1/1, 1/2, 1/3, 1/4,...)

Time

Space

\( s=0 \)

\( s=2 \)

Slope

\( s=-1 \)

\( s=-2 \)

Slope

\( 1/1 \)

\( 1/2 \)

\( 1/3 \)

\( 1/4 \)

\( 1/5 \)

\( 1/6 \)

\( 1/7 \)

\( 1/8 \)

\( 1/9 \)

\( 1/10 \)
Unit 1
Fig. 8.5
Pile-up:
One 60mph car hits five standing cars
**Fig. 8.5**

Pile-up: One 60mph car hits five standing cars.

**Fig. 8.6**

Pile-up: Five 60mph cars hit one standing car.
Fig. 8.5
Pile-up:
One 60mph car
hits
five standing cars

Fig. 8.6
Pile-up:
Five 60mph cars
hit
one standing cars

Fig. 8.7
Pile-up:
Five 60mph cars
hit
five standing cars

(Fug-gedda-aboud-dit!!)

(Many possible scenarios depending on initial positions!)
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Super-elastic examples: This really is “Rocket-Science”
Rocket Science!
0th: \( V(0) = 1/10 = 0.1 \)  
1st: \( V(1) = 1/10 + 1/9 = 0.211 \)  
2nd: \( V(2) = 1/10 + 1/9 + 1/8 = 0.336 \)  
3rd: \( V(3) = V(2) + 1/7 = 0.478 \)  
4th: \( V(4) = V(3) + 1/6 = 0.646 \)  
5th: \( V(5) = V(4) + 1/5 = 0.846 \)  
6th: \( V(6) = V(5) + 1/4 = 1.096 \)  
7th: \( V(7) = V(6) + 1/3 = 1.429 \)  
8th: \( V(8) = V(7) + 1/2 = 1.929 \)
By calculus: \(M \cdot \Delta V = -v_e \cdot \Delta M\) or: \(dV = -v_e \frac{dM}{M}\) Integrate: \(\int_{V_{IN}}^{V_{FIN}} dV = -v_e \int_{M_{IN}}^{M_{FIN}} \frac{dM}{M}\)
By calculus: \( M \cdot \Delta V = -v_e \cdot \Delta M \)  

or: \( dV = -v_e \frac{dM}{M} \)  

Integrate: \( \int_{V_{IN}}^{V_{FIN}} dV = -v_e \int_{M_{IN}}^{M_{FIN}} \frac{dM}{M} \)

\[ V_{FIN} - V_{IN} = -v_e \left[ \ln M_{FIN} - \ln M_{IN} \right] = v_e \left[ \ln M_{IN} M_{FIN} \right] \]
A Thales construction for momentum-energy

(Made obsolete by Estrangian scaling to circular \((V_1,V_2)\) plots. Still, one has to construct \(\sqrt{m_1/m_2}\) slopes.)
This is a detailed construction of the energy ellipse in a Largangian \((v_1,v_2)\) plot given the initial \((v_1,v_2)\).

The Estrangian \((V_1,V_2)\) plot makes the \((v_1,v_2)\) plot and this construction obsolete.

(Easier to just draw circle through initial \((V_1,V_2)\).)