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

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)

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 $m_1, m_2, m_3, \ldots$ 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”
Potential energy dynamics of Superballs and related things

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- Super-elastic examples: This really is “Rocket-Science”
If superball was a balloon its bounce force law would be linear $F = -k \cdot x$ (Hooke Law)

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

$\approx P \cdot \pi 2Rx$

Thales' geometry and "Sagittal†" approx.

† "bow"
**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)*

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

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

$$= kx$$

Thales' geometry and "Sagittal" appox.
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)

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

$\approx P \cdot \pi 2Rx = P \cdot 2\pi Rx$ (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?)

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

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?)

\[
\text{Volume}(X) = \int_0^X \pi r^2 \, dx = \int_0^X \pi x(2R - x) \, dx = \int_0^X 2R \pi x \, dx - \int_0^X \pi x^2 \, dx = R \pi X^2 - \frac{\pi X^3}{3} \approx \begin{cases} 
R\pi X^2 & (\text{for } X \ll R) \\
\frac{4}{3}\pi R^3 & (\text{for } X = 2R)
\end{cases}
\]

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


(Ahead on...)

Unit 1
Fig. 7.1 (modified)
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Total energy \( E = mgh \)

Height \( h \)

Force is weight \( mg \) only

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

Total energy \( E = mgh \)

Height \( h \)

1990 BounceIt Mac simulations

Details of each case follows using newer Web simulations

(a) Drop height
(Zero kinetic energy)

(b) Maximum kinetic energy
(Zero total force)

Unit 1
Fig. 7.2

Floor force balances weight \( mg \)

(c) Maximum penetration
(Zero kinetic energy again)

Force is maximum

Maximum penetration \( x_{\text{max}} \)

Maximum Force \( F(x_{\text{max}}) \)

Total energy \( E \)
(a) Drop height $h$
(Zero kinetic energy)

Total Force curve $F(x) + mg$

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

Force is weight $mg$ only

Drop Height $h$

Display of Force vector using similar triangle construction based on the slope of potential curve.

http://www.uark.edu/ua/modphys/markup/BounceItWeb.html
(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.
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Force $F(x)$ and Potential $U(x)$ for soft heavy non-linear superball

Total Energy $E = Mg h$

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

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

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

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

- $U_{\text{total}}(y) = -Mg + U^{\text{ball}}(y)$
- $F_{\text{total}}(y) = Mg + F^{\text{ball}}(y)$

**Total Energy** $E = Mg \cdot h$

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

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

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

Total Energy $E = Mgh$

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

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

**Unit 1 Fig. 7.5**

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

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

$y_{\text{max}} \quad (+) \quad y_{\text{static}} \quad (-) \quad y = h$

$F^{\text{total}}(h)$

$F_{\text{areas cancel}}$

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

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

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

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

$F(t) = \frac{dP(t)}{dt}$
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Bouncing columns and Newton’s cradle

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

Super-elastic examples: This really is “Rocket-Science”
Main Control Panel

- Let mouse set: \((x,y,Vx,Vy)\)
- Let mouse set force: \(F(t)\)
- Plot solid paths
- Plot dotted paths
- Plot no paths
- Plot \(V1\) vs. \(V2\)
- Plot \(Y1(t), Y2(t)\)
- Plot PE of \(m1\) vs. \(Y1\)
- Plot \(V2\) vs. \(V1\)
- Plot user defined i.e. \(Y1\) vs. \(Y2\)
- Balls initially falling
- Balls initially fixed
- No preset initial values

Number of masses
- 1 Ball

Acceleration of gravity
- 0.5 \(100 \times \text{cm/s}^2\)

Collision friction (Viscosity)
- 0 \(10^\text{g}\)

Initial gap between balls
- 5.45 \(10^\text{g}\)

Force power law exponent
- 1

Force Constant
- 500

Canvas Aspect Ratio - W/H i.e. 0.75 & 1.0
- 0.75

Sets gravity

This is linear setting (increase for non-linear)

y Max =
- 7

Initial x1 =
- 0.5

Max x PE plot =
- 0.5

F-Vector scale =
- 0.003

Error step =
- 0.000

\(m1= 1 \times 10^2\)

\(V1_0= 0 \times 10^2\)

http://www.uark.edu/ua/modphys/markup/BounceItWeb.html

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

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

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

\[ F(t) = \frac{dP(t)}{dt} \]
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Super-elastic examples: This really is “Rocket-Science”
(a) Force $F(Y)$ Units Mg (N)

- **Hard** $F = -kHx$
  - $f_Y = -16y - 1$ 
  - Gently increasing Force
  - $f_Y = -2y - 1$
  - Gently increasing Force

- **Soft** $F = -k_x$
  - $f_Y = -16y - 1$
  - Gently increasing Force
  - $f_Y = -2y - 1$
  - Gently increasing Force

(b) Potential $U(Y)$ Units of MgY (J)

- **Rapidly growing slope** $u(y) = 8y^2 + y$
  - $U = 3$
  - $u = 2$
  - $u = 1$

- **Gently constant slope** (Pure gravity) $u(y) = y$
  - $U = 3$
  - $u = 2$
  - $u = 1$

(c) Force $F(Y)$ Units Mg (N)

- **Hard** $F = -kHx$
  - $f_Y = -16y - 1$
  - Gently increasing Force
  - $f_Y = -2y - 1$
  - Gently increasing Force

- **Soft** $F = -k_x$
  - $f_Y = -16y - 1$
  - Gently increasing Force
  - $f_Y = -2y - 1$
  - Gently increasing Force

(d) Potential $U(Y)$ Units of MgY (J)

- **Rapidly growing slope** $u(y) = 8y^2 + y$
  - $U = 3$
  - $u = 2$
  - $u = 1$

- **Gently constant slope** (Pure gravity) $u(y) = y$
  - $U = 3$
  - $u = 2$
  - $u = 1$

(e) Geometry of Linear Force with Constant Mg and Quadratic Potential

- $F(Y) = -kY - Mg$
  - $U(Y) = (1/2)kY^2 + MgY$

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

- $U_{Total} = U_{grav} + U_{target}$
  - $U_{grav} = Mg \frac{y}{2} (y \geq 0)$
  - $U_{target} = Mg \frac{y + 1}{2} kY^2 (y < 0)$

**Close view of Soft** $F = -k_x$

- $f_Y = -(1/2)y - 1$
  - $f_Y = -16y - 1$
  - Gently increasing Force

- **Note dashed curve followed by PE minimum. Parabola? What?**
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**Force $F(x)$ and Potential $U(x)$ for soft heavy non-linear superball**

Unit 1 Fig. 7.5

Bounce effects due to the flat part of non-linear $F(y)$

$\begin{align*}
F_{total}(y) &= -Mg + F_{ball}(y) \\
U_{total}(y) &= -Mgx + U_{ball}(y)
\end{align*}$

Total Energy $E = Mg\cdot h$

$\begin{align*}
U_{total}(y_{max}) &= \int_{y_{static}}^{y_{max}} F_{total}(y) \, dy + \int_{y=h}^{y_{static}} F_{total}(y) \, dy + U(h) = U(h) = E \\
Work &= W = \int F(x) \, dx = Energy \, acquired = Area \, of \, F(x) = -U(x) \\
Impulse &= P = \int F(t) \, dt = Momentum \, acquired = Area \, of \, F(t) = P(t)
\end{align*}$

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

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(Simulations)

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

Parable allegory for Livermore
Fancy&overpriced “political” approach

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Velocity amplification
or “throw” factor = 2.5
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
(about equal to RumpCo finite gap experiment)

Unit 1
Fig. 7.6
Cooperation between *Los Alamos* and *Livermore* yields insight to answer “What’s going on?”

[Graph showing linear, quadratic, and quartic functions with corresponding equations: F(y) = y^4, F(y) = y^2, F(y) = y^1.]

**Figure 7.7**

Unit 1

**Equations:**
- \( V_2 = 1.03 \)
- \( V_1 = 0.996 \)
Velocity amplification
or “throw” factor = 1.03
(practically “no-throw”)
for linear force \( F(y) = ky \)

Cooperation between Los Alamos and Livermore yields insight to answer “What's going on?”

Flat part of non-linear force gives “explosive” effect
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Velocity Amplification in Collision Experiments...and some results of “Project-Ball”
Involving Superballs

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University of Southern California
Los Angeles, California 90007
(Received 25 September 1969; revised 25 September 1970)

If a pen is stuck in a hard rubber ball and dropped from a certain height, the pen may bounce to several times that height. The results of two such experiments, which can easily be duplicated in any undergraduate physics laboratory, are plotted for a range of mass ratios. A simple theoretical discussion which provides a qualitative understanding of the phenomenon is presented. A more complicated formulation which agrees very well with one of the experiments is also presented. The latter involves a simple analog computer program. Finally, an intriguing generalization of the phenomenon is considered.

INTRODUCTION

1 Trade name of product by Whammo Manufacturing Co., San Gabriel, Calif.

Shortly after the well-known Superball 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 ejecting the pen.

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.

ACKNOWLEDGMENT


We would like to thank John C. Fakan, John E. Heigway, and John H. Marburger for help during the initial and final stages of this project.

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.

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
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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.
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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 $$$$$ product. Invited us to visit. Yay! $$$$
A story of USC pre-meds visiting Whammo Manufacturing Co.

...and some results of “Project-Ball”

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Still a little sad, we return to Rm 69.
Somebody drops a box of balls that immediately bounce into the wet paint.
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The rest is history.
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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 $G(x)$.

Fto. 10. Sagittal formula.
A story of USC pre-meds visiting Whammo Manufacturing Co.

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Then fancy-pants computer theory can predict N-ball tower bounce
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Measuring spot-size \( d \) gives energy vs. height.
Slope of \( E(x) \) gives force \( F(x) \) and \( G(x) \).

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.
Then fancy-pants computer theory can predict N-ball tower bounces

Here are some 3-ball tower bounce predictions

Class of W. G. Harter

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

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

Fancy-pants computer theory fits experiment better

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

AJP Volume 39 / 661

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.

662 / June 1971
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Super-elastic examples: This really is “Rocket-Science”
Unit 1
Fig. 8.1a-c
Independent Bang Model (IBM)
3-Body Geometry
(a) Quartic Force
\[ F(y) = ky^4 \]

- \[ m_3 = 10 \text{ kg} \]
- \[ m_2 = 30 \text{ kg} \]
- \[ m_1 = 100 \text{ kg} \]

\[ \text{Initial Velocities} \]
- \[ v_3 = -1 \text{ m/s} \]
- \[ v_2 = -1 \text{ m/s} \]
- \[ v_1 = -1 \text{ m/s} \]

\[ \text{Final Velocities} \]
- \[ v_3 = 3.41 \text{ m/s} \]
- \[ v_2 = 0.701 \text{ m/s} \]
- \[ v_1 = 0.298 \text{ m/s} \]

(b) Independent Collisions (Independent of Force Law)

- \[ v_3 = -1 \text{ m/s} \]
- \[ v_2 = -1 \text{ m/s} \]
- \[ v_1 = -1 \text{ m/s} \]

\[ \text{Initial Velocities} \]
- \[ v_3 = 3.5 \text{ m/s} \]
- \[ v_2 = 0.538 \text{ m/s} \]
- \[ v_1 = 0.077 \text{ m/s} \]

\[ \text{Final Velocities} \]
- \[ v_3 = 3.41 \text{ m/s} \]
- \[ v_2 = 0.701 \text{ m/s} \]
- \[ v_1 = 0.298 \text{ m/s} \]

(c) Linear Force
\[ F(y) = ky \]

- \[ m_3 = 18 \text{ kg} \]
- \[ m_2 = 30 \text{ kg} \]
- \[ m_1 = 100 \text{ kg} \]

\[ \text{Initial Velocities} \]
- \[ v_3 = -1 \text{ m/s} \]
- \[ v_2 = -1 \text{ m/s} \]
- \[ v_1 = -1 \text{ m/s} \]

\[ \text{Final Velocities} \]
- \[ v_3 = 1.48 \text{ m/s} \]
- \[ v_2 = 1.32 \text{ m/s} \]
- \[ v_1 = 0.81 \text{ m/s} \]
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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.

small&fast... impedance matched to... BIG&SLOW

*J. B. Hart and R. B. Herrmann, Amer. J. Phys. 36, 46 (1968).*
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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

<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>7×10^7</td>
<td>10</td>
<td>10^7 years</td>
</tr>
<tr>
<td>triple-alpha process</td>
<td>helium</td>
<td>carbon, oxygen</td>
<td>2×10^8</td>
<td>2000</td>
<td>10^6 years</td>
</tr>
<tr>
<td>carbon burning process</td>
<td>carbon</td>
<td>Ne, Na, Mg, Al</td>
<td>8×10^8</td>
<td>10^6</td>
<td>10^3 years</td>
</tr>
<tr>
<td>neon burning process</td>
<td>neon</td>
<td>O, Mg</td>
<td>1.6×10^9</td>
<td>10^7</td>
<td>3 years</td>
</tr>
<tr>
<td>oxygen burning process</td>
<td>oxygen</td>
<td>Si, S, Ar, Ca</td>
<td>1.8×10^9</td>
<td>10^7</td>
<td>0.3 years</td>
</tr>
<tr>
<td>silicon burning process</td>
<td>silicon</td>
<td>nickel (decays into iron)</td>
<td>2.5×10^9</td>
<td>10^8</td>
<td>5 days</td>
</tr>
</tbody>
</table>
A story of Stirling Colgate (Palmolive) and core-collapse supernovae

Source
http://hubblesite.org/newscenter/archive/releases/2007/10/image/a/

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<td>2000</td>
<td>10⁶ years</td>
</tr>
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<td>10³ years</td>
</tr>
<tr>
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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 re-invigorated by neutrino interaction. The surrounding material is blasted away (f), leaving only a degenerate remnant.
Stirling Colgate
From Wikipedia, the free encyclopedia

**Stirling Auchincloss 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 Auchincloss 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.

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

---

---

velocity amplification

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

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

(Now I have to pay APS for my own paper.)
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(a) Constant force $F=-k$ (linear potential $V=kx$)

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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

4-Equal-Body

"Shockwave" or pulse wave Dynamics

Opposite of continuous wave dynamics introduced in Unit 2

http://www.uark.edu/ua/modphys/testing/markup/BounceItWeb.html
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Speeding car and five stationary cars

(V_M(0) = 60, V_m(1) = 0)

V_M(01) = 30

V_M(012) = 20

V_M(0123) = 15

V_M(01234) = 12

V_M(012345) = 10

Unit 1

Fig. 8.5

Pile-up:

One 60mph car hits five standing cars
Unit 1

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. 8.5
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!)

Unit 1

Five speeding cars and five stationary cars
($V_M(0) = 60, V_{m(1)} = 0$)

$V_M(01) = 30$

$V_M(012) = 20$

$V_M(0123) = 15$

$V_M(01234) = 12$

$V_M(012345) = 10$

Five speeding cars and a stationary car
($V_M(1) = 60, V_{m(0)} = 0$)

$V_M(10) = 30$

$V_M(210) = 40$

$V_M(3210) = 45$

$V_M(43210) = 48$

$V_M(543210) = 50$
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Rocket Science!

Unit 1
Fig. 8.8a-b

\[ m\Delta v_7 + 3m\Delta V_M(7) = 0 \]

\[ m\Delta v_6 + 4m\Delta V_M(6) = 0 \]

\[ m\Delta v_5 + 5m\Delta V_M(5) = 0 \]

\[ m\Delta v_4 + 6m\Delta V_M(4) = 0 \]

\[ m\Delta v_3 + 7m\Delta V_M(3) = 0 \]

\[ m\Delta v_2 + 8m\Delta V_M(2) = 0 \]

\[ m\Delta v_1 + 9m\Delta V_M(1) = 0 \]

\[ m\Delta v_0 + 10m\Delta V_M(0) = 0 \]
0th: $V(0)=1/10=0.1$

3rd: $V(3)=V(2)+1/7=0.478$

6th: $V(6)=V(5)+1/4=1.096$

1st: $V(1)=1/10+1/9=0.211$

4th: $V(4)=V(3)+1/6=0.646$

7th: $V(7)=V(6)+1/3=1.429$

2nd: $V(2)=1/10+1/9+1/8=0.336$

5th: $V(5)=V(4)+1/5=0.846$

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

\( v_e \) known as “Specific Impulse”
By calculus: $M \cdot \Delta V = -v_e \cdot \Delta M$  

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

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

The Rocket Equation:  

$$V_{FIN} - V_{IN} = -v_e \left[ \ln M_{FIN} - \ln M_{IN} \right] = v_e \left[ \ln \frac{M_{IN}}{M_{FIN}} \right]$$
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 Lagrangian \((v_1, v_2)\) 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 \((V_1, V_2)\).)