The Physics in Science Fiction Movies , Batman, The Dark Knight

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ABSTRACT

The movie "The Dark Knight" offers a thrilling platform for the application of physics in famous movies. With numerous action sequences like intense chases, violent crashes, gravity-defying leaps, and explosive interactions, the movie offers a diverse take on physics in science fiction and superhero movies. This in-depth investigation of these sequences offers insight into the artistic view that the filmmakers take with the laws of physics. Bad physics is often used as a device to improve the entire cinematic experience. Therefore, this analysis seeks to identify both good and bad examples of physics in "The Dark Knight." By doing so, we seek to analyze the effects of inaccurate physics on the movie and how they shape the narrative and spectacle of this film.

1. Introduction

The second movie in the batman trilogy is set a year after the events in Batman Begins (2005) where Gotham city is experiencing an unusual peace as Batman, Lieutenant James Gordon, and newly appointed District Attorney Harvey Dent collaborate successfully to put criminals behind bars. However, they all face a new and dangerous challenge as a mysterious and sadistic mastermind called "The Joker" appears and creates a new wave of mayhem. The Joker during an intense bank robbery, steals all of the Gotham's mob money. He uses this money to stage a series of horrific and strategic attacks against the city and its people, each one carefully planned and aimed at Dent and Batman. Batman's battle with the Joker rapidly intensifies and becomes deeply personal which forces him to "confront everything he believes". Additionally, a love triangle between Bruce Wayne, Harvey Dent and Rachel Dawes. The joker next plan causes results in a tragic turn of events as the Batman and Commissioner Gordon are forced to choose between saving Rachel or Harvey. This eventually results in Rachel's death and Dent's severe disfigurement. The Joker strategically uses Harvey's damaged emotions to transform him to the vengeful two-faced.

While batman eventually manages to catch the joker after one of his massacres, he realizes the Joker's intentions: the turning of Harvey Dent. Commissioner Gordan and Batman are forced confront Harvey who is consumed by rage and blames Gordon for Rachel's death. The confrontation tragically results in Dent's demise. Gordan and Batman are faced with the difficult decision of uncovering Dent's recent actions and risk losing the city's hope and justice. Batman takes responsibility for Dent's crimes. His sacrifice saves Dent's reputation as the city's savior. The film concludes with Batman on the run, facing the consequences of his decisions and leaving the city in a state of uncertainty.

The movie "The Dark Knight" offers a thrilling platform for the application of physics in famous movies. With numerous action sequences like intense chases, violent crashes, gravity-defying leaps, and explosive interactions, the movie offers a diverse take on physics in science fiction and superhero movies. This in-depth investigation of these sequences offers insight into the artistic view that the filmmakers take with the laws of physics. Bad physics is often used as a device to improve the entire cinematic experience. Therefore, this analysis seeks to identify both good and bad examples of physics in "The Dark Knight." By doing so, we seek to analyze the effects of inaccurate physics on the movie and how they shape the narrative and spectacle of this film.

2. Good Physics

2.1. Scene 1: Bullet Denting the Truck

In car chase scene under the bridge, the Joker (Heath Ledger) shoots at the SWAT truck which contains Harvey Dent (Aaron Eckhart). Using the first gun (Glock 17), the Joker shoots at the SWAT Truck. In the next scene inside the car, it can be observed that the Joker has managed to make indents in the walls of the armored steal truck. Afterwards, the Joker uses his second (Remington 870 sawed-off) and third (Bazooka) gun to shoot at the truck after finishing his ammo.

Harvey Dent then asks the officer in the SWAT truck "These things are made for that right?" and the officer replies "He'll need something a lot bigger to get through this" The real question is whether the Joker's gun would actually have enough energy to dent the SWAT truck?

To prove that this scene included good and correct physics, the gun range and its energy right before hitting the truck is calculated.

While in the scene that is being analyzed, the Joker is standing and shooting, the picture bellow can be used to estimate the trucks distance from the ground and later using that information, the bullet's distance to the ground when shooting the bullet can be estimated. Using Logger Pro, the scale was set using the truck's height (excluding the wheels) which is around 2.7 m. The height between the ground and the layer which the Joker is standing on is around 0.91m.

It is assumed that the Joker holds the gun straight in his hands and his hand makes a 90° angle with his body, as observed in the picture bellow. Using Heath Ledger's height, 1.85m, the height of the gun in the Joker's hand from the truck's ground was estimated to be around 1.56m. Therefore, this and the previous information can be used to calculate the bullet's total distance from the ground.

$$\Delta d_{y_{bullet}} = \Delta d_{\text{Truck floor}-\text{Ground}} + \Delta d_{\text{Gun}-\text{Ground}}$$

$$\Delta d_{y_{bullet}} = 0.91 + 1.56$$

$$\Delta d_{y_{bullet}} = 2.47\text{m}$$

Vertical and Horizontal analysis to calculate the horizontal range of the bullet:

Vertical ↑ +	Horizontal → +
$\vec{v_1}_y = 0\frac{m}{s}$ [up] Assuming that the Glock 17 was shot horizontally $\Delta\vec{d_y} = -2.47\ m\ [up]$ Since the bullet's velocity was far too great to be able to calculate the gravitational potential energy, the value is estimated. $\vec{a} = -9.8\ \frac{m}{s^2}\ [up]$ $t = ?$	The average muzzle velocity of a Glock 17 gun is approximately 375 $\frac{m}{s}$ $\vec{v_1}_x = 375\frac{m}{s}$ [left] $t = 0.71$ s $\Delta\vec{d_x} = ?$
$\Delta\vec{d} = \frac{1}{2}\vec{a}\Delta t^2 + \vec{v_1}\Delta t$ $-2.47 = \frac{1}{2}(-9.8)t^2$ $t = \sqrt{\frac{(-2.47)(2)}{(-9.8)}}$ $\mathbf{t = 0.71s}$	$\vec{v} = \frac{\Delta\vec{d}}{\Delta\vec{t}}$ $375 = \frac{\Delta\vec{d_x}}{0.71}$ $\underline{\mathbf{\Delta\vec{d_x} = 266.25m\ [right]}}$

The distance between Joker's truck and the SWAT truck is approximately 10m. Therefore, the bullet's range was calculated to be 270m which can easily reach the SWAT truck. The range calculated for the Glock 17 is also similar to its real "effective" range which is roughly around 60m. The difference between these two values is due to the fact that air resistance was seen as negligible in the calculations and the range is from the moment the gun is shot to the moment it hits the ground while the real value is only the effective range. This also conclude that the bullets velocity when hitting the SWAT truck is greater than it would be if it was farther away from the other truck.

The second part of the calculations is to prove whether the bullet will be able to dent the SWAT truck's wall. This is done by calculating the muzzle energy of the gun to see if it can damage the steel walls of the truck. But first, the bullets velocity when hitting the SWAT truck is calculated using the kinematic equations.

The bullet's mass (m bullet) estimated by using the mass of the bullet typically used for the Glock 17. The distance between the SWAT truck and Joker's Truck was also estimated using values found online. The time it took for the bullets to hit the truck was calculated using Adobe Premiere and the time interval between the two bullets making contact with the SWAT truck were calculated. Next the time it took for the joker to pull the triger was calculated and this value was subtracted from the other value. The Δt calculated is the true time it took for the bullet to hit the SWAT truck after being released.

$$m_{bullet} \approx 90\ \text{gr} = 0.09\text{kg}$$

$$\vec{v_1} = 375 \frac{m}{s}\ [\text{left}]$$

$$\Delta\vec{d} \approx 10\ \text{m}$$

$$\Delta t = 0.04\text{s}$$

$$\vec{v_2} = ?$$

$$\Delta\vec{d} = \left(\frac{\vec{v_1}+\vec{v_2}}{2}\right)\Delta t$$

$$10 = \left(\frac{375+\vec{v_2}}{2}\right)(0.04)$$

$$v_2 = 125 \frac{m}{s}$$

Next, using the velocity, the bullet's kinetic energy is calculated.

$$E_k = \frac{1}{2} m.v_2^2$$

$$E_k = \frac{1}{2}(0.09)(125^2)$$

$$\underline{\mathbf{E_k = 703.125\ J}}$$

Therefore, the kinetic energy also known as the "muzzle energy" of the Glock 17 is approximately 700 J, assuming that the mass of each bullet is 0.09kg.

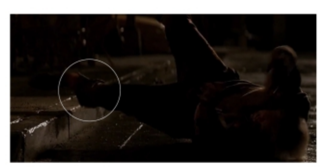
The SWAT truck's material is hardened steel with thicknesses varying from 3.17 mm to greater than 6.35 mm depending on the level of resistance required to build most of the body. For this specific scene, it is assumed that the wall's thickness is around 4.5mm. According to MyArmoury.com, it takes around 400J to dent a 3.00mm truck made of steel. And by further calculations it can be estimated that 600J (400×4.5÷3.00) of energy is needed to dent the 4.5mm thick SWAT truck. This value is very close to the bullet's kinetic energy (700 J). In conclusion, this physics is a good explanation of how the Joker's bullet was able to reach the SWAT truck from his own truck and make an indent inside the SWAT truck's walls in a way that it can be visible from inside.

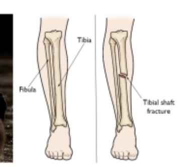
2.2. Scene 2: Maroni's Legs Breaking from a Fall

During one of the scenes, Batman (Christian Bale) interrogates Maroni (portrayed by Eric Roberts), demanding information about the Joker's whereabouts and hold Maroni over the edge of a balcony. The exchange is intense, and Maroni mocks Batman, saying that the vigilante won't kill him because of his moral code. He also says that "A fall from this height won't kill me" and the Batman replies, "I'm counting on it" and drops Maroni. The scene concludes with Maroni falling and hitting the ground with a slight angle and breaking his legs.

The batman believed that the fall from that height would only injure Maroni and won't kill him. Therefore, this analysis will prove whether his statement was true and if the force from the ground acting upon Maroni's feet were enough to break his legs.

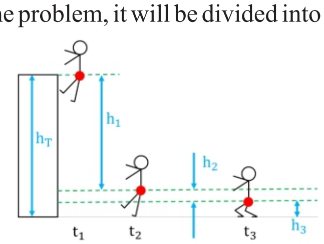
Falling from different heights result in minor or severe injuries, they can cause fractures in certain situations. For example, if a person falls directly on a hard surface, such as concrete or pavement, that can easily cause a Tibia fracture. This also seems to be the case for Maroni's injury.





The comprehensive force per area necessary to break the tibia in the lower leg is estimated to be around 1.6×108 N/m^2 . Additionally, the smallest cross-sectional area of the tibia is around 3.2×10−4 m^2 which is slightly above the ankle.

To simplify the calculations, the person is considered a point located at his center of mass which is located slightly below the belly-button. It is also assumed that the acceleration during this time is negative and constant. To analyze the problem, it will be divided into different parts.



First, the average force of the ground on Maroni's legs during the impact will be calculated. For the time interval between t1 and t2, the final velocity can be calculated using Kinematic 2D and the Work-Energy Theorem. However, due to the moving camera angle, this value cannot be analyzed using applications such as Logger Pro. Therefore, we will use the Work-Energy approach. According to the law of conservation of energy, assuming that the force of friction is negligible, we have:

$$E_{T_1} = E_{T_2}$$

$$E_{g_1} + E_{k_1} = E_{g_2} + E_{k_2}$$

E_{k1}= 0 (The initial velocity is zero because the batman was holding Maroni over the edge of the balcony and simply dropped him).
Knowing that $h_T = h_1 + h_2 + h_3$ the equation above can be simplified into this equation:

$$mgh_1 = \frac{1}{2}mv_2^2 \qquad \text{(a)}$$

Next, the time interval between t_2 and t_3 is considered. This time, there is work being done, which is a contact force from the floor on the person. Its direction is the opposite direction to the displacement which is why the contact force does negative work. This negative work is:

$$W_{ground, person} = -F_{floor}h_2$$

Using the Work-Energy Theorem we get:

$$W = \Delta E$$

$$F_{floor}h_2 = E_{k_2} + E_{g_2}$$

$$F_{floor}h_2 = \frac{1}{2}mv_2^2 + mgh_2$$

h_2 refers to the time right before and after impact. The change in potential energy is mgh_2
Now this equation is rearranged using equation (a)

$$F_{floor}h_2 = mgh_1 + mgh_2$$

$$F_{floor} = \frac{mg\,(h_1 + h_2)}{h_2}$$

$$F_{floor} = mg(\frac{h_1}{h_2} + 1) \qquad \text{(b)}$$

Using this formula, the value of F_{floor} is calculated.

$$m_{Maroni} = 75 \text{ kg}$$

$$g = 9.8\ \frac{m}{s^2}$$

h_1= Maroni's height from waist up subtracted from the average height of a second-floor balcony above ground (=15 ft) which was calculated using Logger Pro using the same method from "Scene 1: Bullet denting the truck"

$$h_1 = 4.57 \text{ m}$$

$$h_2 = 0.06 \text{ m}$$

$$F_{floor} = (75)(9.8)\,(\frac{4.57}{0.06} + 1)$$

$$F_{floor} = 5.7 \times 10^4 \text{N}$$

5.7×10^4N is the force acting on Maroni's legs

2.2.1. Calculating the Real Force Needed to Break a Person's Legs

The maximum force that the tibia can withstand: $1.6{\times}10^8$ N/m^2
Smallest cross-sectional area of the tibia: $3.2{\times}10^{-2}$ m^2
The value is multiplied by 2 because the force is acting on both legs :

$$F_{max} = (1.6 \times 10^8)(3.2 \times 10^{-4}\ m^2)(2)$$

$$F_{max} = 5.12 \times 10^4 \text{ N}$$

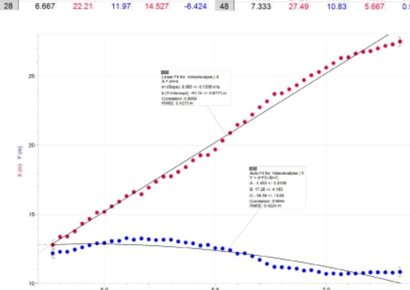
Since the force acting on Maroni's legs in the movie is larger than the minimum force needed to break the leg's tibia ($F_{max} < F_{floor}$). In conclusion, using the Work-Energy Theorem, it can be proven that this scene from the movie portrays accurate physics. Maroni would most likely break his legs as a result of that fall and would not suffer other life-threatening injuries based on the way he landed n his feet with his bent at a very slight angle. This slight angle evidently decreased his chances of getting more injuries which was proven during the analysis above.

2.3. Scene 3: Truck Knocked Out of Its Path

In this scene, the Joker tries to capture Harvey Dent to create disorder and mayhem in Gotham City. Many police and SWAT cars are driving around the area. The Joker and his thugs are trying to control the region and eliminate the police. The Joker's truck hits one of the SWAT cars. The force exerted by the truck on the SWAT car is displayed accurately. The SWAT car changes directions and falls into a body of water. This scene demonstrates good physics.

After the Joker's truck hits the SWAT car, it ventures off to the side of the road and ultimately lands in a body of water. The scene shows an accurate representation of a projectile following a parabolic trajectory. The force of gravity is displayed as the object falls into the water at a reasonable time. The following data is from a portion of the fall, starting from the initial fall.

	VideoAnalysis				
	Time (s)	X (m)	Y (m)	X Velocity (m/s)	Y Velocity (m/s)
12	6.133	16.61	13.17	5.001	0.134
13	6.167	16.45	13.25	6.476	-0.068
14	6.200	16.93	13.19	10.806	-0.893
15	6.233	17.35	13.14	10.420	-0.508
16	6.267	17.73	13.17	7.469	-0.444
17	6.300	17.75	13.17	6.893	-1.711
18	6.333	18.07	13.03	9.473	-2.582
19	6.367	18.42	12.95	11.239	-2.365
20	6.400	18.89	12.90	11.088	-2.712
21	6.433	19.27	12.74	8.045	-2.211
22	6.467	19.29	12.79	8.820	-2.783
23	6.500	19.69	12.56	14.017	-3.489
24	6.533	20.33	12.53	16.383	-3.250
25	6.567	20.88	12.40	15.942	-4.391
26	6.600	21.47	12.16	13.266	-3.703
27	6.633	21.68	12.18	12.571	-4.046
28	6.667	22.21	11.97	14.527	-6.424
29	6.700	22.74	11.71	14.161	-7.485
30	6.733	23.17	11.41	12.959	-6.645
31	6.767	23.70	11.20	9.388	-3.999
32	6.800	23.75	11.17	7.157	-2.103
33	6.833	24.04	11.12	8.457	-1.834
34	6.867	24.34	11.07	9.540	-2.229
35	6.900	24.71	10.94	10.082	-1.929
36	6.933	25.05	10.96	9.123	-2.056
37	6.967	25.29	10.83	8.858	-2.845
38	7.000	25.61	10.70	9.302	-1.708
39	7.033	25.93	10.72	9.117	-0.663
40	7.067	26.30	10.67	6.915	0.000
41	7.100	26.35	10.72	5.456	0.557
42	7.133	26.62	10.72	5.121	0.597
43	7.167	26.75	10.75	3.714	0.905
44	7.200	26.80	10.80	3.971	0.645
45	7.233	26.99	10.80	4.834	0.155
46	7.267	27.18	10.80	4.655	-0.052
47	7.300	27.28	10.78	4.959	0.323
48	7.333	27.49	10.83	5.667	0.983



The mass of the SWAT truck was estimated to be 4,985 lbs. or 2261.158 kg.

2.3.1. Horizontal Analysis of Logger Pro Calculations (→+)

$$\vec{a} = \frac{\vec{v}_2 - \vec{v}_1}{\Delta t}$$

$$\vec{a} = \frac{23.17 - 12.79}{0.966}$$

$$\vec{a} = 11\ \frac{m}{s^2}\ [\rightarrow]$$

$$m = 2261.158\ kg$$

$$a = 11\ \frac{m}{s^2}\ [\rightarrow]$$

$$F_{net} = ma$$

$$F_{net} = (2261.158)(11)$$

$$F_{net} = 2.5 \times 10^4 N\ [\rightarrow]$$

The force the Joker's truck applied to the SWAT car was approximately 2.5×10^4 N [→].
According to Newton's 3rd law, the action force of the truck acting on the car is equal in magnitude and opposite in direction to the force of the car acting on the truck.

$$F_{net} = ma$$

$$-24{,}872.738 = (15{,}875.733)a$$

$$a = -1.6\ \frac{m}{s^2}\ [\rightarrow]$$

The truck will experience an acceleration of $-1.6\ m/s^2$ [→] due to the crash.
This scene follows Newton's first law of motion. The SWAT car appears to be moving at a uniform velocity and would continue to do so unless acted upon by an external force: Joker's truck car pushing on the SWAT car. The Joker's truck travels at high velocity, visually higher than the SWAT car's velocity. The Joker's truck also has a larger mass than the SWAT car. That means its kinetic energy is much higher and has the ability to cause more destruction to the SWAT car than it would receive, as shown in the scene. The driver's reaction to this force is shown. The driver is wearing a seatbelt to restrain the full effect of the force. The driver still jolts to the side in the direction of the push.

The scene also follows Newton's second law of motion. The Joker's truck causes the SWAT car to accelerate as it exerts a force on the SWAT car. The acceleration of the SWAT car is directly proportional to the force exerted on it and inversely proportional to its mass. The scene demonstrates the law accurately. The SWAT car's velocity increases and changes direction after being pushed by the Joker. This push and ultimate land in the water demonstrates Newton's third law of motion. For every action, there is an equal and opposite reaction. The Joker applies force on the SWAT car and receives that same force back, accelerating both vehicles.

3. Poor Physics

3.1. Scene 1: Rachel and Batman Falling off a Building

In this scene, Rachel and Batman fall out of a high building. The Joker crashes Harvey Dent's fund raiser event at the penthouse of the building below. The Joker threatens Rachel and holds her over the ledge of the building. The Joker lets go of Rachel, and Batman quickly follows her. They both, holding on to each other, slide on the incline of the building, then free fall and land on a car uninjured.
There are two main problems with the scene.
1. Batman and Rachel survive and acquire no injury after enduring a significant fall. The car also appears to have no damage.
2. The calculated free fall time is 11 seconds. This time is very long for Rachel and Batman to land with gravity acting on them.

In this analysis, Batman's protection is neglected, as falling from such height will undermine any influence of such little protection.

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Illinois Center Building (111 East Wacker Drive)
Film Location of Batman's penthouse in free fall scene

$$m_b = 86\ kg\ (Batman's\ weight)$$

$$m_r = 60\ kg\ (Rachel's\ weight)$$

$$F_{net} = F_g$$

$$F_g = mg$$

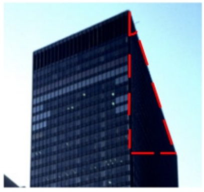
$$F_g = (m_b + m_r) \cdot g$$

$$F_g = (86 + 60) \cdot 9.8$$

$$F_g = 1430.8\ N$$

$$F_g = 1.43 \times 10^3 N$$

This scene breaks the rule of Newton's 3rd law of motion. When Rachel and Batman exert a force of 1430.8 N downwards on the car, an equal force is exerted upwards on Rachel and Batman. A significant and abrupt force on their bodies like this would result in death or severe injury. Rachel and Batman, however, appear fine after the crash. Also, the force applied by Rachel and Batman on the car would likely cause some damage to it. Newton's first law of motion states that an object in motion will stay in motion unless acted upon by another force. Rachel and Batman are falling at a very high velocity to stop their movement; the characters will experience extreme force and acceleration.



3.1.1. Calculations for Real Estimated Time

To solve for time, the initial velocity should be calculated. The initial velocity of this free fall is not zero. Before Rachel and Batman free fall, they slide down the building's incline and gain kinetic energy.

To estimate vertical displacement the Batman and Rachel had, the angle of the slope on which they were sliding was estimated to be around 30° and using this information, the initial velocity was calculated. The initial velocity of the free fall is the final velocity from when Rachel and Batman are sliding. The Joker let's Rachel go, and she slides onto the roof; Batman follows. It is assumed that initial velocity of the sliding part is 0 m/s.

Batman's height: 1.83 m

Rachel's height: 1.75 m

Rachel and Batman slid on the incline roof, holding each other with their arms stretched out. We can see Rachel slide alone on her own before Batman joins her. It appears Rachel slides alone twice her height. Batman comes along and slides a little less than double their height. Batman and Rachel's height were added twice to account for the distance of their arms spread out. These values were added together to find the length of the inclined roof. (Let h represent the length of the hypotenuse)

$$h = 2(1.83 + 1.75 + 1.75)$$
$$= 10.66\ m$$
$$= 11.0\ m$$

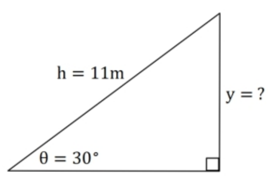
$$\sin 30° = \frac{1}{2}$$

$$\frac{1}{2} = \frac{y}{11}$$

$$11 = 2y$$

$$\frac{11}{2} = y$$

$$y = 5.50\ m$$



Vertical Analysis: [↓] +

$$\Delta\vec{d_y} = 5.5\text{ m } [\downarrow]$$

$$\vec{v_{y_1}} = 0\ \frac{\text{m}}{\text{s}} [\downarrow]$$

$$\vec{a} = 9.8\ \frac{\text{m}}{\text{s}^2} [\downarrow]$$

$$\vec{v_{y_2}} = ?$$

$$2\vec{a}\Delta\vec{d} = v_2^2 - v_1^2$$

$$2(9.8)(5.5) = v_2^2 - 0$$

$$v_2^2 = 107.8$$

$$\mathbf{\vec{v_{y_2}} = 10.4\ \frac{m}{s} [\downarrow]}$$

3.1.2. Free Fall Calculations

Vertical Analysis: [↓] +

$$\vec{v_{y_2}} = 10.4\ \frac{\text{m}}{\text{s}} [\downarrow]$$ (From the previous calculation)

$$\vec{a} = 9.8\ \frac{\text{m}}{\text{s}^2} [\downarrow]$$

$$\Delta\vec{d_y} = 110.3 - 5.5$$

$$\Delta\vec{d_y} = 5.5\text{ m } [\downarrow]$$

$$\Delta t = ?$$

$$\Delta\vec{d} = \frac{1}{2}\vec{a}\Delta t^2 + \vec{v_1}\Delta t$$

$$104.8 = \frac{1}{2}(9.8)t + 10.4t$$

$$0 = \frac{1}{2}(9.8)t + 10.4t - 104.8$$

$$t = 3.68504\ ,\ t \neq -5.80395$$

$$t = 3.69\text{ s}$$

The correct time Rachel and Batman took to free fall is approximately 3.69 seconds.

3.1.3. Rachel and Batman's velocity when hitting the ground

$$2\vec{a}\Delta\vec{d} = v_2^2 - v_1^2$$

$$2(9.8)(104.8) = v_2^2 - 10.4^2$$

$$v_2^2 = 2161.87999996$$

$$\mathbf{\vec{v_{y_2}} = 46\ \frac{m}{s} [\downarrow]}$$

Gravitational potential energy at top of the building, relative to the ground:

$$E_g = mg\Delta h$$
$$= (86 + 60) \cdot 9.8 \cdot 110.3$$
$$= 157{,}817.24\ J$$
$$= 1.6\ \times 10^5\ J$$

Gravitational potential energy at free fall, relative to the ground:

$$E_g = mg\Delta h$$
$$= (86 + 60) \cdot 9.8 \cdot 104.8$$
$$= 1.50\ \times 10^5\ J$$

Gravitational potential energy at landing (relative to the car's height):

$$E_g = mg\Delta h$$
$$= (86 + 60) \cdot 9.8 \cdot 0$$
$$= 0.00\ J$$

Kinetic energy when hitting the ground:

$$E_k = \frac{1}{2}mv^2$$
$$= \frac{1}{2}(86 + 60)46^2$$
$$= 154{,}468\text{ J}$$
$$= 1.50\ \times 10^5\ J$$

Kinetic energy at start of free fall:

$$E_k = \frac{1}{2}mv^2$$
$$= \frac{1}{2}(86 + 60)10.4^2$$
$$= 7.9\ \times 10^3\ J$$

Kinetic energy at top of the building (before joker lets go of Rachel):

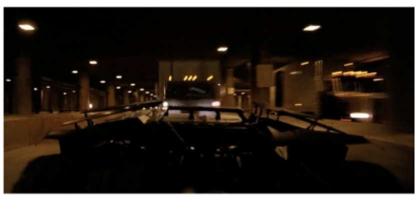
$$E_k = \frac{1}{2}mv^2$$
$$= \frac{1}{2}(86+60)\ (0)$$
$$= 0\ J$$

At the top of the building, the gravitational potential energy of Rachel and Batman is very high. As they free fall, their gravitational potential energy decreases and their kinetic energy increases. Their kinetic energy is highest when they land and lowest at the very top of the building. This sudden landing is dangerous, and landing with such high kinetic energy will result in injury as your body will take in the impact forces, leading to death or severe injuries. Rachel and Batman experience nothing realistic.

The use of poor physics in this scene creates suspense. Throughout the exaggerated time Rachel and Batman free fall, the audience anticipates their harm. The suspense of their survival adds thrill to the scene. Furthermore, when they survive the audience is relieved and witnesses Batman's strength and abilities. And the impression is given that Batman saved Rachel. Overcoming the impossible and using poor physics allows Batman to execute his superpowers. Using poor physics allowed the directors to add more thrill and action to the movie. If Rachel and Batman were to fall from a much smaller distance or at a smaller time, the suspense and anticipation would be less. Using poor physics shows Batman's true capabilities.

3.2. Scene 2: Joker and the Batman Crashing Head-on

In this scene, the Joker tries to hijack the police vehicle to capture Harvey Dent. The Joker is in the trailer area of the truck, shooting missiles. Joker's thugs are also in the truck. One of the thugs is driving the vehicle. Driving on the highway, they face Batman head-on. Batman, driving the Batmobile, is trying to stop the Joker. He crashes into him from the opposite direction at what looks to be a similar speed.



Batmobile facing Joker's truck before the crash
Dark Knight, Batman Rises (2008)

When the cars crash, the Batmobile drives the truck up and over the Batmobile, causing the truck to accelerate backwards. The Joker appears to have no injuries or any impact from the crash. Batman and the Batmobile also experienced no injury after the collision. The Batmobile experiences much less, if any, of an impact from this collision.

This scene displays the use of poor physics. First, the Joker and Batman experience no injury or impact from the collision. Second, the Batmobile experiences far less of an impact and is able to bring the truck above itself, then backwards.

(a) (b)
a) Batmobile after the crash Joker's truck after the crash; b)Dark Knight, Batman Rises (2008)

The use of poor physics makes for a thrilling scene. The poor physics in this scene is necessary to show that Batman has special powers. (And within his Batmobile gadgets/tools to overcome the impossible). This scene shows Batman and his Batmobile to have functions that defy the laws of physics. These capabilities, of course, do not exist in real life. But this is what makes Batman a superhero, and this scene helps emphasize Batman's superpowers. Additionally, intense crashes create a fast-paced film that keeps the audience hooked. When Batman and the Joker survive these crashes, the action can continue for longer.

3.2.1. Kinetic Energy of the Vehicles

The Joker's truck and the Batmobile collided head-on. The vehicle that has less kinetic energy should experience the most destruction. In this case, the Batmobile has less kinetic energy; it should experience more damage than the Joker's truck. The kinetic energy of a vehicle depends on its velocity and mass, as $E_k = \frac{1}{2}mv^2$. The truck and the batmobile appear to be travelling around the same speed. The kinetic energies of both vehicles is calculated using the same estimated velocity. The velocity of the car and truck look nearly the same. If there is a slight difference, the demonstration will still prove the inaccuracy of the scene because their masses significantly differ.

The Joker's truck is an ordinary semi-truck with an empty trailer attachment. Semi-trucks attached to an empty trailer have a mass of 35,000 pounds or 15,875.733 kg. The Batmobile weighs 5500 pounds or 2494.758 kg.

In this scene, Batman and the Joker are driving on the highway. Most highways have a speed limit of 100-110 km /hr. Given the intensity of this scene and the probable fact the Joker and Batman were not following the speed limit, it is estimated that the truck and the Batmobile were going 130 km/hr (36.1 m/s).

3.2.2. Kinetic Energy of Joker's Truck: →+

$$v = 36.1\ \frac{\text{m}}{\text{s}}[\rightarrow]$$

$$m = 15{,}875.733\ kg$$

$$E_k = \frac{1}{2}mv^2$$

$$= \frac{1}{2}(15{,}875.733)\cdot 36.1^2$$

$$= 10{,}351{,}069.54\ J$$

$$= 10\times\ 10^7 J$$

3.2.3. Kinetic Energy of Batmobile: ←+

$$v=36.1\ \frac{\text{m}}{\text{s}}[\leftarrow]$$

$$m = 2494.758\ kg$$

$$E_k = \frac{1}{2}mv^2$$

$$= \frac{1}{2}(\ 2494.758)\cdot 36.1^2$$

$$= 1{,}625{,}596.787\ J$$

$$= 1.6\times\ 10^6 J$$

∴The kinetic energy of the Joker's truck is approximately $10\times\ 10^7$j and the kinetic energy of the Batmobile is approximately 1.6×10^6 j.

Since the kinetic energy of the Batmobile is lower, it should take the most destruction. The Batmobile should encounter immense damage, more than the truck, accelerating significantly. The collision should cause the truck and car to accelerate in the opposite direction the Batmobile was initially moving or the same direction the truck was initially moving. The Batmobile does not have enough kinetic energy to cause the truck to move above it.

In addition, this scene breaks Newton's 2nd law of motion: objects with a larger mass require more force to accelerate. The truck holds the larger mass but appears to accelerate more than the Batmobile. The smaller vehicle, the Batmobile, should experience greater acceleration.

Newton's third law states for every action, there is an equal and opposite reaction. The car exerts a force on the truck, and the truck exerts an equal and opposite force on the car. This law is unrepresented in this scene. The Batmobile appears to move forward as it moves the truck over itself. Batman, with control, accelerates his car backwards. The Batmobile would endure immense destruction and uncontrollably accelerate backwards from the force exerted by the truck.

Momentum is the product of the mass and velocity. In the car/truck collision, the vehicles collide inelastically. Momentum is conserved in the system of the car and truck, and the kinetic energy is lost. Kinetic energy is lost in such crashes as it transforms into something else, like destruction in the car/truck or heat. To solve for the final velocity after the objects collide, the law of conservation of momentum. The momentum before the crash is equal to the momentum after the crash. (Directions: →+)

m_t=15,875.733 kg

m_c=2494.758 kg

Momentum before crash = Momentum after crash

$$P_{car} + P_{truck} = P_{ct}$$
$$m_c \cdot \overrightarrow{v_{c_1}} + m_t \overrightarrow{v_{t_1}} = (m_c + m_t)\overrightarrow{v_2}$$
$$v_2 = 26.303147058$$
$$v_2 = 26.3\ \frac{m}{s}\ [\rightarrow]$$

In a car collision, many forces come into play. It is difficult to identify all of these forces and to apply them. For that reason, the calculations for the action and reaction forces of the collision will be provided and other horizontal forces will be ignored. The impulse formula is used to solve for this force exerted on the car and truck.

$$F_{c,t} = F_{t,c}$$
$$\Delta v_t = v_{t2} - v_{t1}$$
$$= 26.303147058 - 36.1111$$
$$= -9.8\frac{m}{s}$$
$$F = \frac{\Delta p}{\Delta t}$$
$$F_{c,t} = \frac{m\Delta v}{\Delta t}$$
$$= \frac{15{,}875.733 \cdot (-9.8)}{0.2}$$
$$= \frac{-155{,}708.4}{0.2}$$
$$= -778{,}542\ N\ [\rightarrow]$$
$$F_{c,t} = 7.8 \times 10^5 N\ [\leftarrow]$$

$$\Delta v_c = v_{c2} - v_{c1}$$
$$= 26.303147058 - (-36.1111)$$
$$= 62.41424705\ m/s$$
$$= 62\ m/s$$

$$\Delta p = F\Delta t$$
$$F = \frac{\Delta p}{\Delta t}$$
$$F_{t,c} = \frac{m\Delta v}{\Delta t}$$
$$= \frac{(2494.758)(62.41424705)}{0.2}$$
$$= 778{,}542\ N\ [\rightarrow]$$
$$F_{t,c} = 7.8 \times 10^5 N\ [\rightarrow]$$

The force of the truck acting on the car is 7.8×10^5 N[→] and the force of the car acting on the truck is 7.8×10^5 N [→]

Newton's first law states that an object will remain at rest or at constant velocity unless acted on by an external force. The joker before the crash was standing in the middle of the trailer. The Joker moves at the same velocity as the truck. At the crash, there was a sudden acceleration as the car moved backwards. The joker, because of his inertia and Newton's first law, will continue to move forward within the trailer at the same velocity. The Joker will be introduced to an external force, the front wall of the trailer, and collide with it. A head on collision with such speed would have the Joker experiencing significant force. Following the crash, the Joker appears to have endured no trauma. Head-on collisions, like the one in this scene, are the most dangerous type of car accidents, often accounting for the highest death toll of all types of car accidents. For the Joker to appear completely unharmed, as if nothing has happened, is beyond unrealistic and demonstrates poor physics.

In addition, Batman, just like Joker, should feel the force from this head on collision. The force of impact doubles because the truck and Batmobiles velocity is combined. According to the estimated velocity, each car was traveling at 130 km/h or 36.1 m/s. That means, the impact force would be that of a collision where the velocity was 260 km/h or 72.2 m/s. And with the kinetic energy of the truck being higher than the Batmobile, the Batmobile would acquire more damage. Therefore, for Batman to endure no life-threatening injury, let alone come out of this crash alive, is virtually impossible.

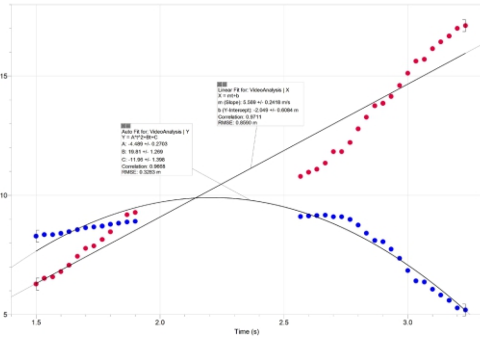
3.3. Scene 3: Batmobile Jumping Over Another Car

The scene involves the Batmobile (also known as the Tumbler) in a high-speed chase with the Joker's truck. As the pursuit intensifies, there's a moment where the Batmobile executes its boost thrusters and manages to jump over a car while landing safely and continuing the chase. This scene demonstrates the agility and advanced technology behind the Batmobile's design. During this time, the joker aims a Bazooka towards a SWAT truck and fires. However, the Batmobile manages to get in between the SWAT truck and the incoming rocket. A great explosion occurs when the rocket makes contact with the Batmobile but the Batmobile does not alter its course and its armor does not seem to take much damage from the impact. Eventually the Batmobile lands in front of the car it was jumping over safely. Remarkably, as the smoke clears, the Batmobile reaches the ground unscathed, having not only absorbed the rocket but also landed safely in front of the car it initially soared over. To analyze the Batmobile's stunt, the motion is divided into its projectile motion when jumping over the car and the impact it suffers from the rocket.

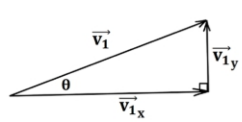
The following graph represents the projectile motion of the Batmobile while jumping over the car. The graph was made using Logger Pro and the Batmobile was considered a point located at its center of mass. However, the Batmobile's movement can only be partially tracked since multiple camera angles are used to capture the scene. As a result, there are gaps in the graph before and amidst the projectile motion, and thus can only be used to analyze the movement.

First, the projectile motion of the car will be analyzed. It is assumed that the boosters stop working after giving the Batmobile its initial velocity as the flames of the boost thrusters were not visible in later scenes.

The Batmobile's starting angle was calculated with a protractor using a shot showcasing the side of the vehicle while jumping ($\theta \approx 13°$) .

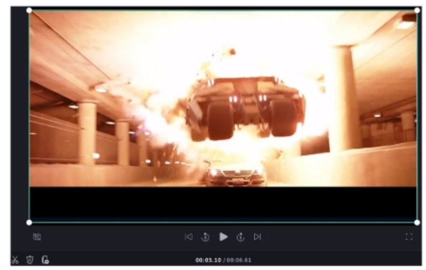


The Batmobile can reach the velocity of 102 m/s with its boost thrusters and by assuming this was its velocity during the motion, the vertical and horizontal velocity can be calculated.

Vertical ↑+	Horizontal →+
$\vec{v_1}_y = 102\sin 13$ $\vec{v_1}_y = 22.945\frac{m}{s}$ [up] $\vec{a} = -9.8\frac{m}{s^2}$ [up] $\Delta\overrightarrow{d_{y_{max}}} = ?$ [up] $\Delta\vec{d}_y = 0m$ [up] $t = ?$	$\vec{v_1}_x = 102\cos 13$ $\vec{v_1}_x = 99.386\frac{m}{s}$ [right] $t = 4.682s$ $\Delta\overrightarrow{d_x} = ?$ m [right]
$2\vec{a}\Delta\vec{d} = v_2^2 - v_1^2$ $2(-9.8)\Delta\vec{d} = 0 - 22.945^2$ $\Delta\overrightarrow{d_{y_{max}}} = 26.86m$ The maximum height of the Batmobile from the ground. Movement from the start until ($v = 0\frac{m}{s}$)	$\vec{v} = \frac{\Delta\vec{d}}{\Delta\vec{t}}$ $99.386 = \frac{\Delta\vec{d}}{4.682}$ $\Delta\overrightarrow{d_x} = 21.22m$ [right] The horizontal distance that the Batmobile can take according to its initial velocity and time.
$\Delta\vec{d} = \frac{1}{2}\vec{a}\Delta t^2 + \vec{v_1}\Delta t$ $0 = \frac{1}{2}(-9.8)t^2 + 22.945t$ $0 = t(-4.9t + 22.945)$ $t = 0s$ $t \approx 4.682s$ The time it takes for the Batmobile to finish the projectile motion	

The car that the Batmobile jumped over is a Touareg SUV 2008 with the height of 1.726m, and the maximum height that the Batmobile could jump over was well over that range. It can be concluded that the Batmobile would be able to jump over the car using its boost thrusters. The time needed to complete the movement was calculated to be around 4.7s. However, the time it took from the moment the car left the ground until it made contact with the ground was 6.61s in the movie. This scene was lengthened for exaggeration and a few explosions were added to make the scene exciting for viewers. Next, the horizontal range for the car was calculated to be around 21.22m with the time of 4.7s. Since the horizontal displacement of the Batmobile in the movie was less than 10m, the time and horizontal displacement in the movie is illogical and it can be said without a doubt that this scene included poor physics.

While the Batmobile was in mid-air, the Joker shot a rocket at it with a bazooka. A bazooka rocket could penetrate as much as 0.127 m of armour plate. The rocket contains approximately 6.65 megajoules of explosive energy. However advanced Batman's technology seems, it is very unlikely that he would be able to survive that blast without a scratch. Additionally, the Batmobile's armour did not suffer much damage from the explosion and the only real damage that was done was to the back wheels. In later scenes, the Batmobile easily transformed into a motorbike which did not look slightly damaged. Even if the Batmobile's armour was strong enough to withstand the explosion, the force of the rocket should have changed its direction which is another instance of poor physics in this scene.



Although this scene is visually pleasing and exciting for viewers, it does not follow the laws of physics. The use of poor physics in movies, particularly in action sequences such as this one, is often intentional. The directors add impossible effects to adrenaline-filled scenes for cinematic purposes. In this case, the use of boost thrusters and the jump over a car contributes to the overall spectacle. By exaggerating the capabilities of the Batmobile, viewers subconsciously engage with the narrative as they try to accept the exaggerated reality presented on screen. The longer some exciting scenes last, the more people will become immersed in the scene. Additionally, the Batmobile is a fictional vehicle designed by Bruce Wayne (Batman) which showcases advanced technology. By finishing impossible tasks such as surviving a direct hit from a rocket without significant damage, the filmmakers highlight the indestructible nature of Batman's technology which also reinforces the idea that Batman is a powerful superhero. It is also implied that although the Batman might suffer a few losses along the way, he is overall indestructible and cannot be beaten easily.

While the scene may follow the laws of physics, its main focus is to entertain and immerse the audience in the world of Gotham City and Batman. The use of poor physics is for creating a thrilling cinematic experience rather than aiming for strict realism.

4. Conclusion

Poor physics creates a dramatic and suspenseful effect. Using good physics may not be as engaging for the audience as it can look less exciting. Using poor physics allows the directors and writers of the film to be more creative and explore scenes beyond reality. Superhero movies are a great example of this.

This movie showcases many incidents of good and poor physics. Poor physics can enhance movies to make a simple action scene look more phenomenal than it actually is. Due to this it is normal to see strange sequences and can be easily identified as not following simple physics laws. Christopher Nolan loves to exaggerate his movies, especially in The Dark Knight, by adding extra explosions, high technology and insanely high free fall scenes to blow the audience's mind. However, some accurate physics is also included to ensure that the movie is not too unrealistic for the audience. A balance between the two parts is what makes an action movie worth watching. After all, some of the best scenes in the film industry are those that greatly defy every day physics.

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