Introduction

Physics 211
Syracuse University, Physics 211 Spring 2016
Walter Freeman

January 19, 2017

The beginning: Free fall

My purpose is to set forth a very new science dealing with a very ancient subject. There is, in nature, perhaps nothing older than motion, concerning which the books written by philosophers are neither few nor small nevertheless I have discovered by experiment some properties of it which are worth knowing and which have not hitherto been either observed or demonstrated....

So far as I know, no one has yet pointed out that the distances traversed, during equal intervals of time, by a body falling from rest, stand to one another **in the same ratio as the odd numbers beginning with unity.**

–Galileo Galilei, *Dialogues and Mathematical Demonstrations Concerning Two New Sciences*, 1638

Reminders:

- Webpage: https://walterfreeman.github.io/phy211/
  - Syllabus, homework, etc. are all there
- The first homework is due next Wednesday

"Ask a Physicist"

There are a lot of cool things in physics that go beyond mechanics.

If you've got questions you'd like me to address, send them in and I'll answer them!

- What are gravity waves?
- How is physics used in medicine?
- What's the Large Hadron Collider for?
- How does a touchscreen work?
- How do 3D movies work?
- What is the Higgs boson?
- How is physics used in video games?
- How does a nuclear bomb work?
- How does a supercomputer work?

Homework tips

Your first homework assignment is due Wednesday.

- Make use of words, pictures, and algebra (not just algebra!) in your reasoning
- We're interested in how you think, not just the answer
- Physical values need to be given with units ("4 meters", not "4")
- Leave variables in until the very end
- Paper is cheap – don't cramp yourself!

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- Leave variables in until the very end
- Paper is cheap – don't cramp yourself!

- Ask for help – early and often
  - Email: wafreema@syr.edu
  - Facebook group
  - Office hours
  - the Physics Clinic
  - Recitations
  - In class!

The course webpage and Facebook page

- All notes, etc., will be posted on the course website (not Blackboard)
- I will also post course announcements there
- The syllabus is posted there
- You really should read the section on the course philosophy

- There is also a course Facebook page at `https://www.facebook.com/groups/234894186963170/`
- ... or search "Syracuse University Physics 211, Spring 2017"
- Joining the group doesn't mean anyone else can see your private posts, etc., or that you can see theirs
- This is a great place to ask questions, get advice, and collaborate with your classmates
- Up to 2% extra credit for those who help their peers

Office hours

In the Physics Clinic (for now):

- Tuesdays: 5:10-6:50 PM
- Fridays: 9:30-11:30 AM
- Other times announced (if homework is due Friday, I may hold Thursday office hours)

or by appointment.

Outside these times you might find me in the Clinic or in my office in room 215.

Dimensions

Things in nature aren't just described by numbers; they have an associated *dimension*, and we measure them using a *system of units*.

We have three different kinds of dimension:

- **Length**: usually measured in **meters**; also inches, miles, light-years...
- **Mass**: usually measured in **kilograms**; also grams, tonnes...
- **Time**: usually measured in **seconds**; also hours, days...

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For the Americans: the pound measures *force*, not mass. The word "weight" means "force due to gravity"; an object with a mass of one kilogram weighs 2.2 pounds on Earth.

Math, physics-style, I: working with dimensions

"It is two hours from Syracuse to Adirondack State Park"

Does this statement make sense?

A: Yes

B: No

"It is two hours from Syracuse to Adirondack State Park"

Does this statement make sense?

A: Yes

B: No

C: Only if I tell you something else, too

Math, physics-style, I: working with dimensions

"It is two hours from Syracuse to Adirondack State Park"

Does this statement make sense?

A: Yes

B: No

C: Only if I tell you something else, too

I've got to also tell you the car's velocity!

"The distance from Syracuse to the Adirondacks is two hours"

$$\text{Distance} = \text{Time}$$

This statement makes no sense!

"The distance from Syracuse to the Adirondacks is two hours"

$$\text{Distance} = \text{Time}$$

This statement makes no sense!

"The distance from 'Cuse to the Adirondacks is two hours at 100 km per hour"

$$\text{Distance} = \text{Time} \times \frac{\text{Distance}}{\text{Time}}$$

Here the dimensions match on both sides; this is a valid statement.

Math, physics-style, II: working with units

Units of measure (km, hours) follow the rules of algebra.

$$s = (2\,\text{hr}) \times \frac{100\,\text{km}}{1\,\text{hr}}$$
$$s = 200\,\text{km}$$

Velocity is thus a length divided by a time: km/hr, m/s, etc. What about acceleration?

Math, physics-style, II: working with units

"A falling object's speed increases by 10 meters per second every second."

$$10\,\frac{\frac{\text{meter}}{\text{second}}}{\text{second}}$$

This is really awkward to write...

$$10\,\frac{\frac{\text{meter}}{\text{second}}}{\text{second}} = 10\text{m}/\text{s}^2$$

Much better! Even though nobody's ever seen a "squared second", this still makes sense mathematically. We can build all kinds of compound units this way.

Newton's second law says that force is equal to mass times acceleration. In symbols, $F = ma$. What units could you measure force in?

A: $\mathrm{kg\,m/s}$

B: $\mathrm{kg\,m/s^2}$

C: $\mathrm{m/s^2}$

D: $\mathrm{kg\,m}$

Math, physics-style, III: compound units

Newton's second law says that force is equal to mass times acceleration. In symbols, $F = ma$. What units could you measure force in?

A: $\mathrm{kg\,m/s}$

B: $\mathrm{kg\,m/s^2}$

C: $\mathrm{m/s^2}$

D: $\mathrm{kg\,m}$

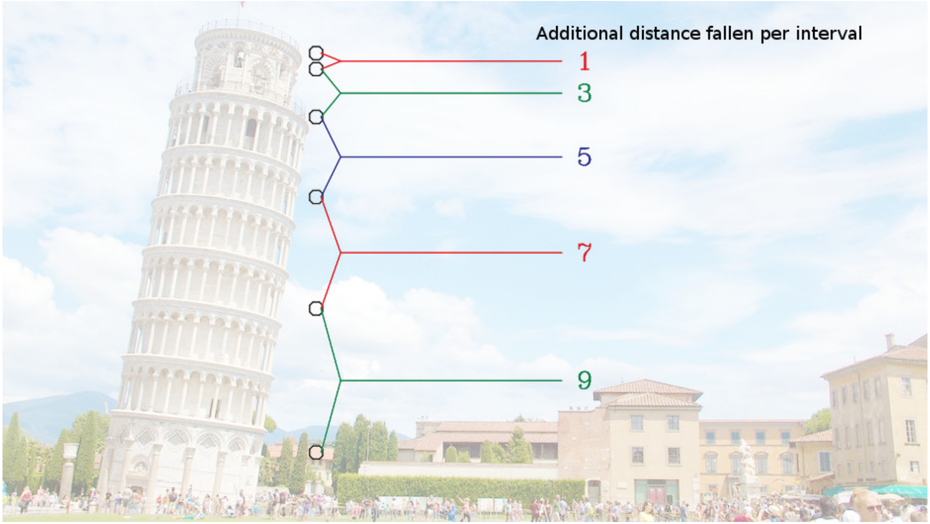
This gets awkward to keep writing, so we define:
$1\,\mathrm{kg\,m/s^2} = 1$ newton, abbreviated N.

The beginning: describing motion (1-D)

Recall that at first, we are only concerned with describing motion.

- Most fundamental question: “where is the object I’m talking about?”
- Quantify position using a “number line” marked in meters:
  - Choose one position to be the origin (“zero”) – anywhere will do
  - Choose one direction to be positive
  - Measure everything relative to that
  - Can measure in any convenient units: centimeters, meters, kilometers...
- You’re used to this already, perhaps:
  - Mile markers on highways
  - Yard lines in American football

The beginning: Free fall



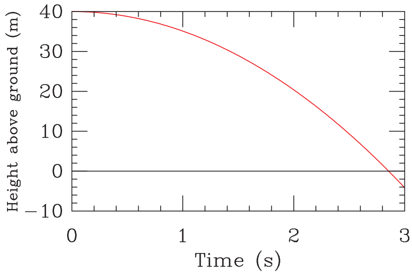
Galileo observed this, but can we explain it?

Equations of motion

Complete description of motion: "Where is my object at each point in time?"

This corresponds to a mathematical function. Two ways to represent these. Suppose I drop a ball off a building, putting the origin at the ground and calling "up" the positive direction:

Graphical representation



Algebraic representation

$$y(t) = (40\,\mathrm{m}) - Ct^2$$

(C is some number; we'll learn what it is Thursday)

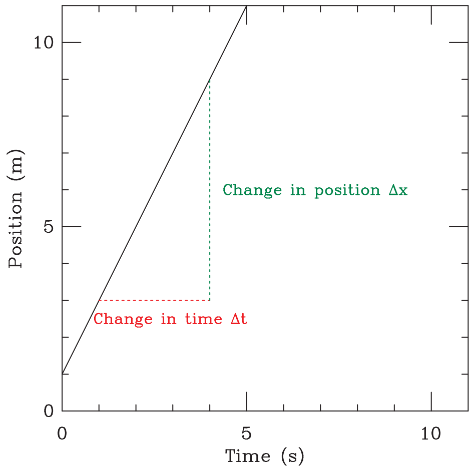
Both let us answer questions like "When does the object hit the ground?"

→ ... the curve's x-intercept

→ ... when $y(t) = 0$

Velocity: how fast position changes

The slope of the position vs. time curve has a special significance. Here's one with a constant slope:



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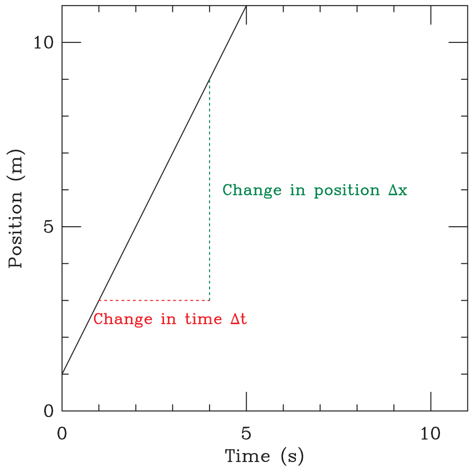

Slope is $\frac{\text{rise}}{\text{run}} = \frac{\Delta x}{\Delta t} = \frac{2\,\text{m}}{1\,\text{s}} = 2$ meters per second (positive; it could well be negative!)

Velocity: how fast position changes

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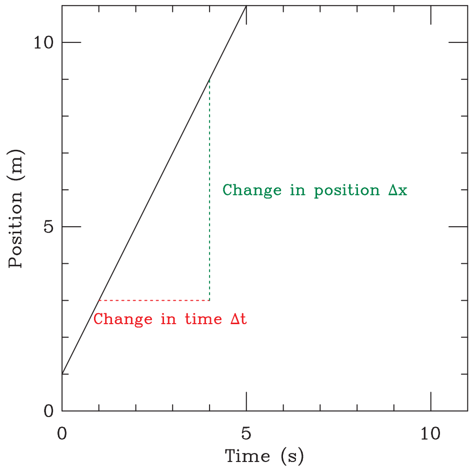
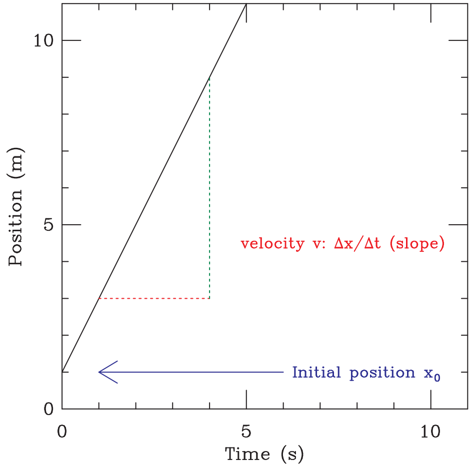


Slope is $\frac{\text{rise}}{\text{run}} = \frac{\Delta x}{\Delta t} = \frac{2\,\text{m}}{1\,\text{s}} = 2$ meters per second (positive; it could well be negative!)

$\rightarrow$ The slope here – change in position over change in time – is the **velocity**! Note that it can be positive or negative, depending on which way the object moves.

Constant-velocity motion: connecting graphs to algebra

If an object moves with constant velocity, its position vs. time graph is a line:



We know the equation of a straight line is is $x = mt + b$ (using t and x as our axes).

- m is the slope, which we identified as the velocity
- b is the vertical intercept, which we recognize as the value of x when $t = 0$

We can thus change the variable names to be more descriptive:

$$x(t) = vt + x_0 \text{ (constant-velocity motion)}$$

Going from "equations of motion" to answers

$x(t) = vt + x_0$ is called an *equation of motion*; in this case, it is valid for constant-velocity motion.

It gives you the same information as a position vs. time graph, but in algebraic form.

To solve real problems, we need to be able to translate physical questions into algebraic statements:

- "If a car starts at milepost 30 and drives at 50 mph, where is it an hour later?"

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To solve real problems, we need to be able to translate physical questions into algebraic statements:

- "If a car starts at milepost 30 and drives at 50 mph, where is it an hour later?"
  - Using $x(t) = x_0 + vt$, with $x_0 = 30\,\text{mi}$ and $v = 50\frac{\text{mi}}{\text{hr}}$, calculate x at $t = 1\,\text{hr}$

Asking the right questions

“I drop an object from a height h. When does it hit the ground?” How do I do this? (Take $x_0 = h$ and upward to be positive.)

Remember, we want to ask a question in terms of our physical variables. This question has the form:

“What is __________ when __________ equals __________?”

Fill in the blanks.

A: v, x, 0
B: t, x, h
C: x, t, 0
D: t, x, 0
E: x, v, 0

Asking the right questions

"At what location do two moving objects meet?"

A: "At what time does $x_1 = x_2$?"
B: "At what time does $v_1 = v_2$?"
C: "What is x_1 at the time when $x_1 = x_2$?"
D: "What is x_1 when $t_1 = t_2$?"

Velocity, acceleration, and calculus

Constant-velocity motion: $x(t) = x_0 + vt$

- Came from looking at the equation of a line
- We can understand this in a different framework, too:

- Velocity is the rate of change of position
  - Graphical representation: Velocity is the slope of the position vs. time graph
  - Mathematical language: Velocity is the derivative of position

We know we need to know about acceleration ("F=ma") – what is it?

- Acceleration is the rate of change of velocity

Position, velocity, and acceleration

$$\text{Position} \xrightarrow[]{\substack{\text{(take the derivative)}\\ \text{take the rate of change of}}} \text{Velocity}$$

Position, velocity, and acceleration

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Kinematics: how does acceleration affect movement?

Newton's law $a = F/m$ tells us that *acceleration* – the second derivative of position – is what results from forces.

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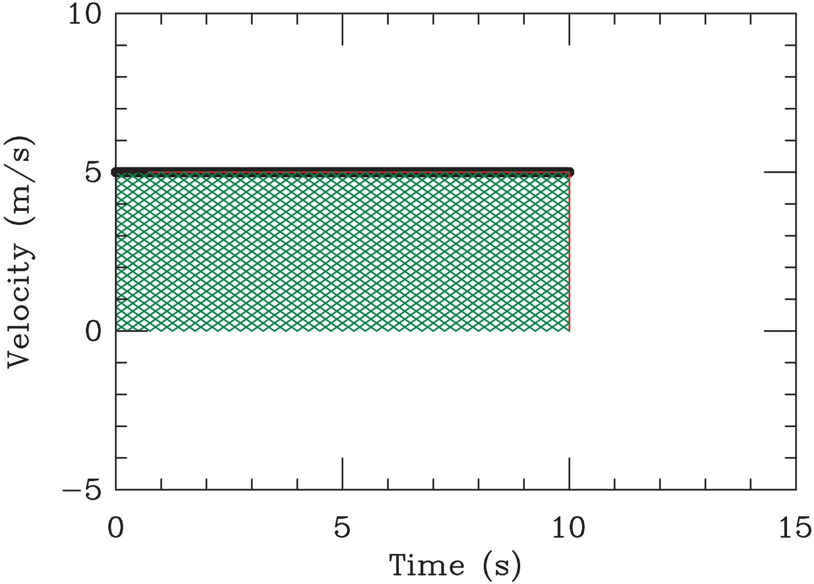
Newton's law $a = F/m$ tells us that *acceleration* – the second derivative of position – is what results from forces.

All freely falling objects have a constant acceleration downward.

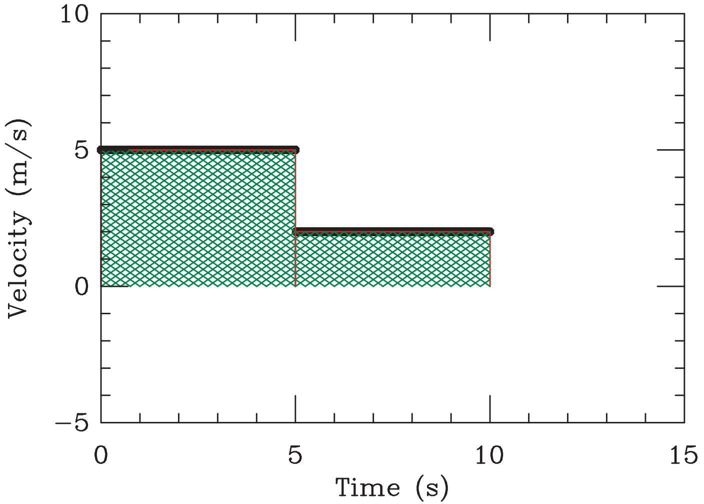
This number is so important we give it a letter: $g = 9.81$ m/s^2

A calculus review

If velocity is the rate of change of position,
why is the area under the v vs. t curve equal to displacement?

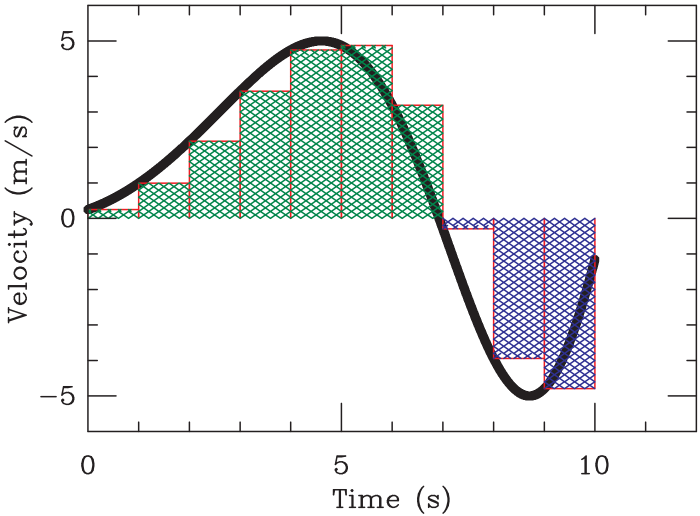


We know $\Delta s = vt$. What is that here? What's the area of the shaded region?



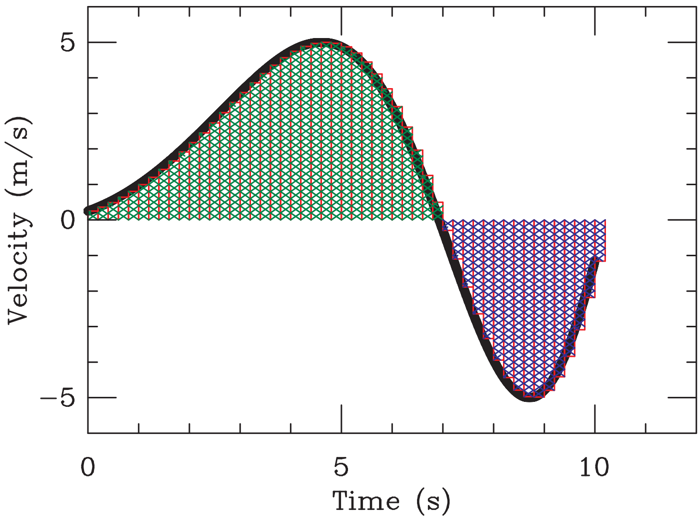
Now what is Δs? What is the area of the shaded region?

A calculus review



Does this work? How do we fix it?

A calculus review



The area between the t-axis and the velocity curve is the distance traveled.
(The area below the t-axis counts negative: "the thing is going backwards"

In calculus notation: $\int v(t)\,dt = \delta x = x(t) - x_0$

Position, velocity, and acceleration

$$\text{Position} \quad \underset{\substack{\text{take the area under the curve of} \\ \text{(take the integral of)}}}{\overset{\substack{\text{(take the derivative of)} \\ \text{take the rate of change of}}}{\rightleftarrows}} \quad \text{Velocity}$$

Position, velocity, and acceleration

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Constant acceleration

Particularly interesting situation:

- Free fall (as you saw)
- Any time the force is constant: $F = ma \to a = F/m$...

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Plan of attack:

- We know what the acceleration curve looks like (it's just flat)
- Figure out the area under the acceleration curve to get the velocity curve
- Figure out the area under the velocity curve to get the position curve

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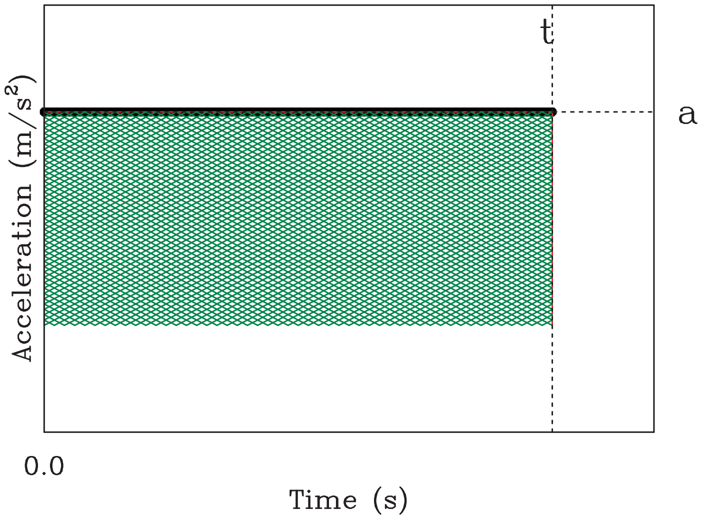
Plan of attack:

- We know what the acceleration curve looks like (it's just flat)
- Figure out the area under the acceleration curve to get the velocity curve
- Figure out the area under the velocity curve to get the position curve

Remember the area under the curve of (velocity, acceleration) just gives the *change in* (position, velocity) – i.e. initial minus final.

We'll start by assuming x_0 and v_0 are zero.

Constant acceleration



What's the area under the curve out to time t, which gives the change in the velocity – $\Delta v = v(t) - v_0$?

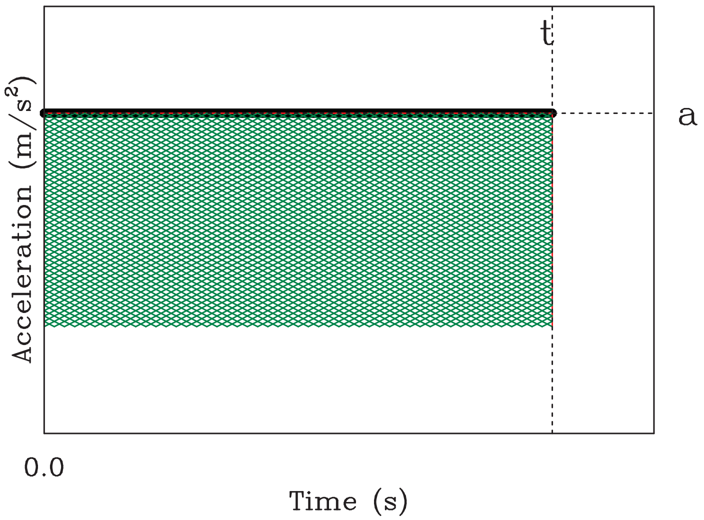
A: $\Delta v = at$

B: $\Delta v = at + v_0$

C: $\Delta v = \frac{1}{2}at^2$

D: $\Delta v = a$

Constant acceleration



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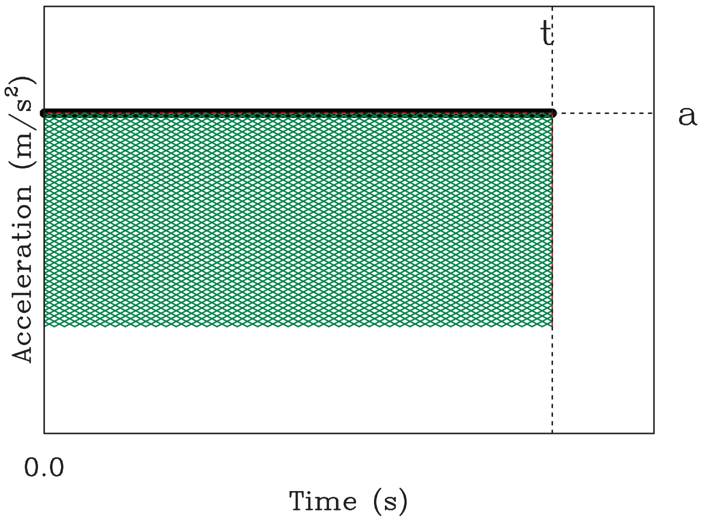
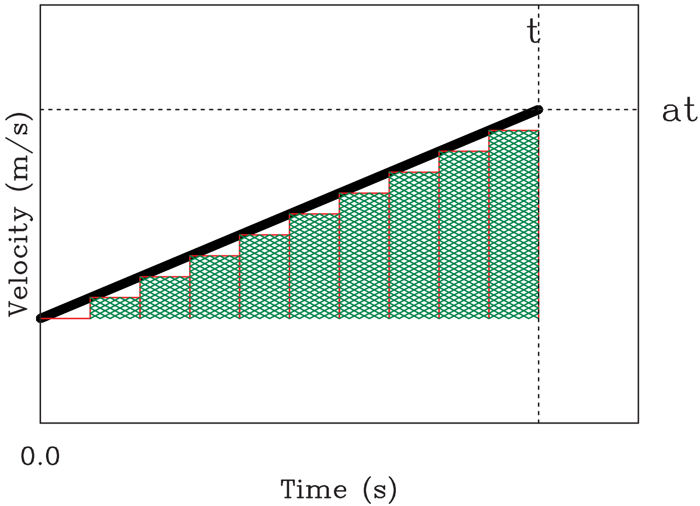
Constant acceleration



What's the area under the curve out to time t, which gives the change in the velocity – $\Delta v = v(t) - v_0$?

Δv, the change in velocity, is $v(t) - v_0 = at$, so $v(t) = at + v_0$

Same thing again to get position



Now the area under the velocity curve gives the change in position: $\Delta x = x(t) - x_0$. What is that?

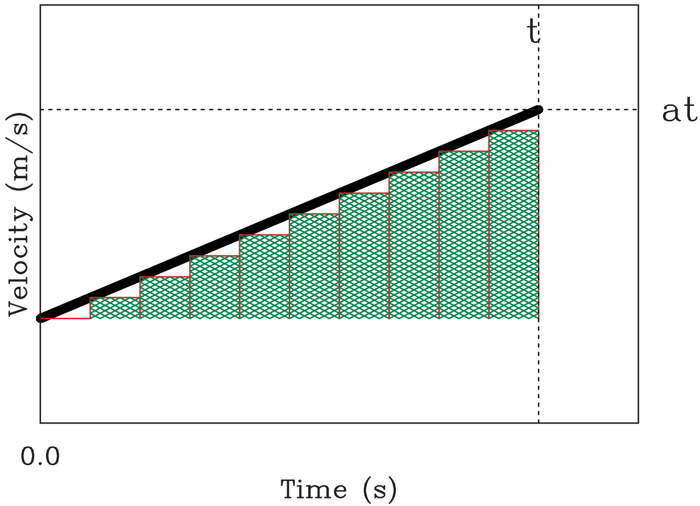
A: $\Delta x = at$

B: $\Delta x = vt$

C: $\Delta x = \frac{1}{2}at^2$

D: $\Delta x = v$

Same thing again to get position



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A: $\Delta x = at$

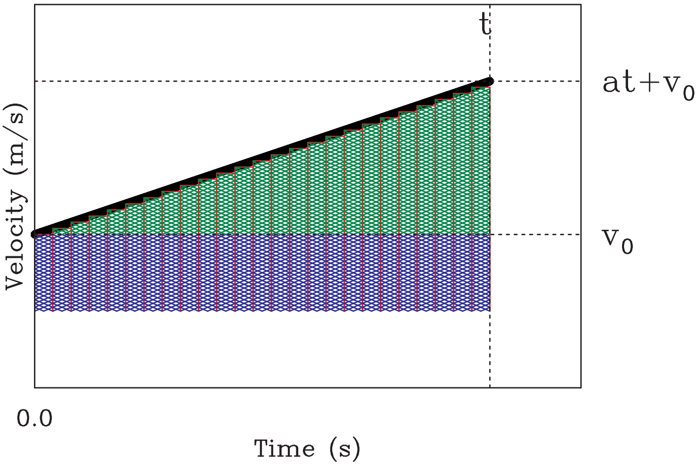
B: $\Delta x = vt$

C: $\Delta x = \frac{1}{2}at^2$

D: $\Delta x = v$

$$x(t) - x_0 = \frac{1}{2}at^2, \text{ thus } x(t) = \frac{1}{2}at + x_0$$

Now if v_0 is not zero...



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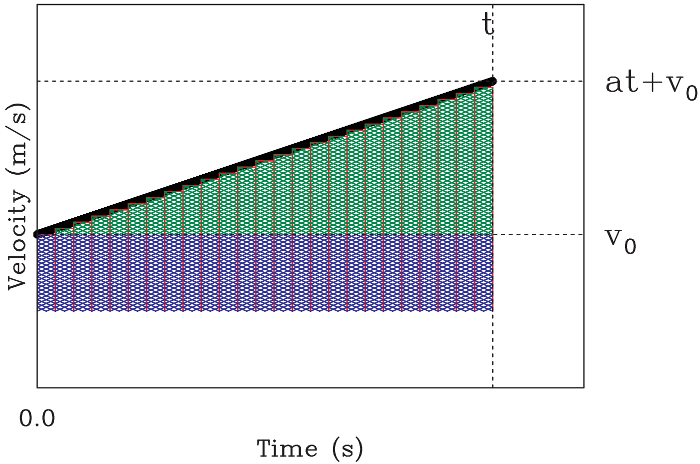


Area under blue part: $v_0 t$
Area under green part: $\frac{1}{2}at^2$
Total change in position: $x(t) - x_0 = \frac{1}{2}at^2 + v_0 t$

Thus, $x(t) = \frac{1}{2}at^2 + v_0 t + x_0$

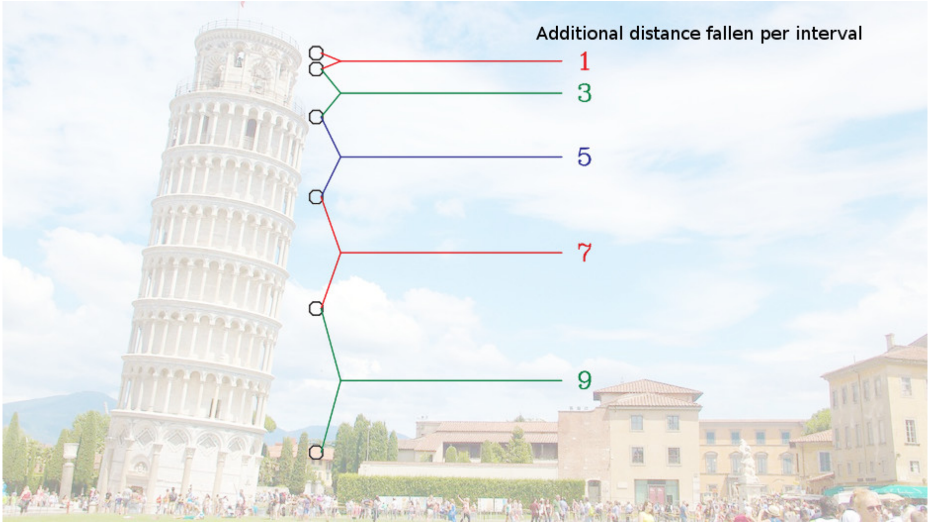
For those who are familiar with calculus:

$$
\begin{aligned}
a(t) &= \text{const.} \\
v(t) &= \int a\,dt &&= at + C_1 \\
x(t) &= \int v\,dt = \int (at + C_1)dt &&= \frac{1}{2}at^2 + C_1 t + C_2
\end{aligned}
$$

A little thought reveals that C_1 is the initial velocity v_0 and C_2 is the initial position x_0. This gives us the things we just derived, but much more easily:

$$
\begin{aligned}
v(t) &= at + v_0 \\
x(t) &= \frac{1}{2}at^2 + v_0 t + x_0
\end{aligned}
$$

Free fall revisited



Adding these numbers together gives us 1, 4, 9, 16, 25...
The calculus above explains this: distance is proportional to *time squared!*

How fast is the ping-pong ball going when it hits the cans?

- Air pressure P: 10^5 newtons per square meter
- Radius of tube r: 2 cm
- Length of tube L: 2 m
- Mass of ping-pong ball m: 3 g
- Final velocity: v_f (we don't know this yet; it's what we want)

Principles that we will use:

- Area $A = \pi r^2$ (from geometry)
- Force due to air pressure $F = PA$ (think about the units: newtons per square meter $\times$ square meters)
- Newton's second law: $F = ma$ (notice: a and A are different!)

Math, physics-style, IV: put in the numbers at the end!

Notice:

- Every quantity, even if we know its numerical value, gets a variable
- Comparing the dimensions of your expressions can be used to verify you're thinking about them correctly
- We could have guessed everything above, except for the factors of π and 2, just from the units!
- **Solve everything algebraically before putting in the numbers!**
  - **This is *much* cleaner**
  - **Your algebraic statements also mean things, and you can think as you go**
- When you finally do put in the numbers, make sure your units match so you can cancel them

Math, physics-style, IV: put in the numbers at the end!

- Find the force in terms of stuff you know: $F = P(\pi r^2)$
- Find the acceleration that force causes using Newton's second law $F = ma$:

$$\pi P r^2 = ma \to a = \frac{\pi P r^2}{m}$$

- Kinematic relations from before: $x(t) = x_0 + v_0 t + \frac{1}{2} a t^2$ and $v(t) = v_0 + at$

1. First: Write down the expressions for $x(t)$ and $v(t)$
   - $x(t) = \frac{1}{2}at^2$ (since v_0 and x_0 both equal zero); we will find a later
   - $v(t) = at$ (since $v_0 = 0$)
2. Second: Ask the right question, in terms of your variables: "What is v at the time when $x = L$?"
3. Third: Do the algebra corresponding to your question.
   - Set $x = L$: $\frac{1}{2}at^2 = L \to t = \sqrt{\frac{2L}{a}}$
   - Find v at that time: $v = at$, so $v = \sqrt{2La}$

In this problem, we have to go a bit beyond kinematics:

$$\pi P r^2 = ma \to a = \frac{\pi P r^2}{m}$$

Substitute this in:

$$
\begin{aligned}
v_f &= \sqrt{\frac{2\pi P L r^2}{m}} \\
v_f &= \sqrt{2 \times \pi \times 10^5\,(\mathrm{N/m^2}) \times (2\,\mathrm{m}) \times (0.02\,\mathrm{m})^2/(0.003\,\mathrm{kg})} \\
v_f &= \sqrt{1.68 \times 10^5\,(\mathrm{N \times m/kg})} = \sqrt{1.68 \times 10^5\,(\mathrm{kg\,m/s^2}) \times \mathrm{m/\,kg}} \\
v_f &= 409\,\mathrm{m/s}
\end{aligned}
$$