Calculus for the Life Sciences

Lecture Notes – Introduction to the Derivative

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Outline

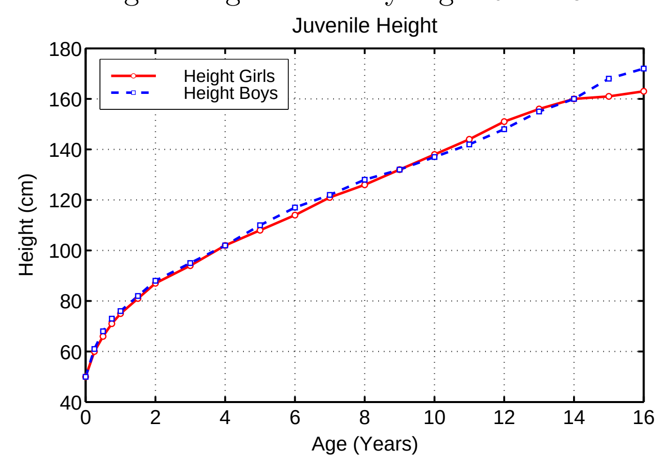
Introduction to the Derivative

Introduction to the Derivative

- The derivative is very important to Calculus
- How to view the Derivative
  - Rate of Growth
  - Velocity
  - Geometric view: The Tangent Line

Juvenile Height 1

Graph of the heights of girls and boys ages 0 to 18



Juvenile Height

- The rate of growth is the slope of the line through the data
  - The earliest years show a high rate of growth
  - Over a wide range of ages, the rate of growth is almost constant
  - The later years show the growth rate slowing
- Growth rate is the difference in heights divided by the difference in time measured in years
- The growth rate $g(t)$ is approximated by the formula

$$g(t_0) = \frac{h(t_1) - h(t_0)}{t_1 - t_0}$$

where t_0 and t_1 are successive ages with heights $h(t_0)$ and $h(t_1)$

Juvenile Height

Growth Rate for Children

Girls age from 2 to 3

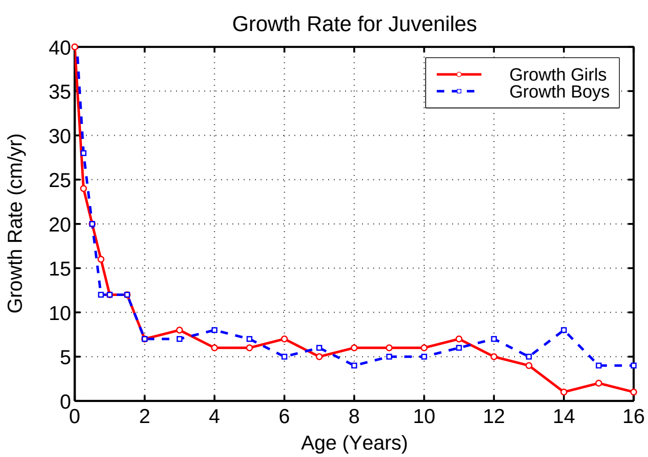
Age (years)	Height (cm)	Annual Growth Rate (cm/yr)
$t_0 = 2$	$h(t_0)$=87	
$t_1 = 3$	$h(t_1) = 94$	$g(2) = \frac{h(3) - h(2)}{3 - 2} = 7$

Boys age 3 months to 6 months

Age (years)	Height (cm)	Annual Growth Rate (cm/yr)
$t_0 = 0.25$ (3 months)	$h(t_0)$=61	
$t_1 = 0.5$ (6 months)	$h(t_1) = 68$	$g(0.25) = \frac{h(0.5) - h(0.25)}{0.5 - 0.25} = 28$

Juvenile Height

Growth Rate for Children



Juvenile Height

Growth Rate for Children

- The growth rate is higher for early years
- Stays almost constant for many years
- Drops almost to zero in the late teens

Example – Growth of a Puppy 1

Developing his Project Calculus course, David Smith measured the growth of his Golden Retriever puppy, Sassafras

Age (days)	Weight (lbs)	Age (days)	Weight (lbs)
0	3.25	101	30
10	4.25	115	37
20	5.5	150	54
30	7	195	65
40	9	230	70
50	11.5	332	75
60	15	436	77
70	19		

Skip Example

Example – Growth of a Puppy 2

Find the average weekly growth rate of the puppy over the first 10 weeks

Solution: 10 weeks is equivalent to 70 days
The weight at day 0 is 3.25 lbs, while its 19 lbs at 10 weeks

The average growth rate is

$$g_{ave} = \frac{19 - 3.25}{10} = 1.575 \text{ lb/week}$$

Estimate the weekly growth rate of the puppy at age 10 weeks using the data at 70 and 101 days

Solution: The weekly growth rate at 10 weeks satisfies

$$g_{ave} = \frac{30 - 19}{(101 - 70)/7} = 2.48 \text{ lb/week}$$

Example – Growth of a Puppy 3

What is the weekly growth rate between days 230 and 436?

Solution: The weekly growth rate between 230 and 436 days satisfies

$$\frac{77 - 70}{(436 - 230)/7} = 0.238 \text{ lb/week}$$

The growth rate increases for several weeks, then slows down as the puppy matures

Example – Growth of a Puppy 4

Graphically we explore:

- The weight of the puppy as a function of age (days)
- The growth in weight per week

The growth curve for the weight of a puppy gives a typical **S-shaped curve**

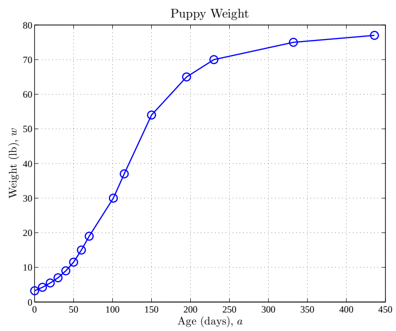
The growth rate curve shows the weight gain accelerating for about 100 days, then slowing down

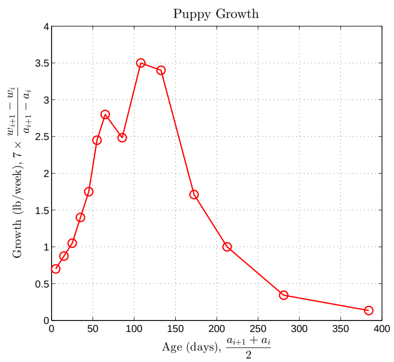
The growth rate is computed between successive data points and associated with the midpoint of the ages ($a_{ave} = (a_{i+1} + a_i)/2$)

$$g(a_{ave}) = 7 \times \frac{w_{i+1} - w_i}{a_{i+1} - a_i},$$

where a_i and w_i are obtained from the growth table. (Graphs follow)

Example – Growth of a Puppy 5





Derivative as a Velocity

Derivative as a Velocity

- Differential Calculus – developed in the 17^{th} century by Sir Isaac Newton and Gottfried Leibnitz to explain the physics of motion
- Velocity of an object is the change in distance divided by the change in time
  - If we travel 200 ft in 10 sec, then we had an average velocity of 20 ft/sec

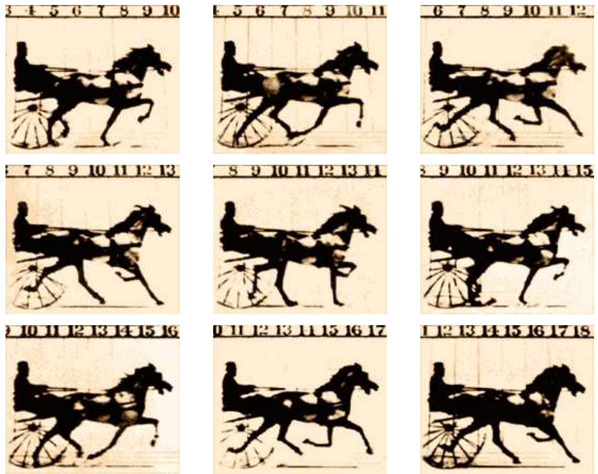
Trotting Horses 1

Eadweard Muybridge – Trotting Horse

- In the 1800s, there was a controversy whether or not a trotting horse ever had all feet off of the ground
- Photographer Eadweard Muybridge developed some special photographic techniques for viewing animals and humans in motion by collecting timed sequences of still pictures
- Viewed in succession with the same intervening times, these pictures produce an animation of motion, which was a precursor to modern motion pictures

Trotting Horses 2

Eadweard Muybridge – Trotting Horse



Trotting Horses 3

Were all feet off the ground at any time?

How fast is the horse trotting?

- Often want to determine how fast a particular animal is running or a bird flying
- How do you determine the speed of a cheetah or the velocity of a peregrine falcon?
- Above sequence of pictures has units of distance (ft) marked in the background and units of time on each frame
- Start by choosing a reference point, say the man's head

Trotting Horses 4

Trotting Horse Speed

The position at $t_0 = 0$ sec, satisfies $s(t_0) = 3.5$ ft, while at $t_1 = 0.04$ sec, the head is at $s(t_1) = 4.5$ ft

$$v(t_0) = \frac{s(t_1) - s(t_0)}{t_1 - t_0} = \frac{4.5 - 3.5}{0.04 - 0} = 25 \text{ ft/sec} \quad = 17.0 \text{ mph}$$

At $t_2 = 0.08$ sec, the head is at $s(t_2) = 5.6$ ft, so the velocity satisfies

$$v(t_1) = \frac{s(t_2) - s(t_1)}{t_2 - t_1} = \frac{5.6 - 4.5}{0.08 - 0.04} = 27.5 \text{ ft/sec} \quad = 18.75 \text{ mph}$$

This is approximately the same

Trotting Horses 5

Trotting Horse Average Speed

The average velocity for the entire sequence of pictures gives the best average velocity for this trotting horse

It is computed by taking the initial and final positions of the head and dividing by the total time between the frames

$$v(t_{ave}) = \frac{s(t_f) - s(t_0)}{t_f - t_0} = \frac{11.5 - 3.5}{0.32 - 0} = 25.0 \text{ ft/sec} \quad = 17.05 \text{ mph}$$

Thus, the velocity is relatively constant over the short time interval of the pictures

Trotting Horses 6

More details

- What if the question asked the velocity of the right front foot?
- Does the right front hoof stop or move backward at any time?
- Current sequence of pictures is inadequate
- How would you answer this question?
- Probably want many more pictures at smaller time intervals
- **This is the limiting process we will undertake to find the derivative**

Example –Ball Falling under the Influence of Gravity 1

A Ball Falling under the Influence of Gravity

A steel ball is dropped from a height of 4 meters and has its height measured every 0.1 seconds

Time (sec)	Distance (cm)	Time (sec)	Distance (cm)
0	0	0.5	123
0.1	5	0.6	176
0.2	19	0.7	240
0.3	44	0.8	313
0.4	78	0.9	396

Falling under the Influence of Gravity 2

Find the average speed of the ball over the 0.9 seconds of the experiment

Solution:

$$v_{ave} = \frac{396 - 0}{0.9 - 0} = 440.0 \text{ cm/sec}$$

Determine the average speed of the ball between 0.5 and 0.7 seconds

Solution:

$$v_{ave} = \frac{240 - 123}{0.7 - 0.5} = 585 \text{ cm/sec}$$

Example – Sky Diving 1

A sky diver encounters a significant amount of air resistance when free falling (and more significantly when the parachute opens), so his speed will not match the parabolic curve characteristic of the Falling Ball

Time (sec)	Height (ft)	Time (sec)	Height (ft)
0	10,000	25	5,763
5	9,633	30	4,733
10	8,797	35	3,703
15	7,811	40	2,673
20	6,791	45	1,643

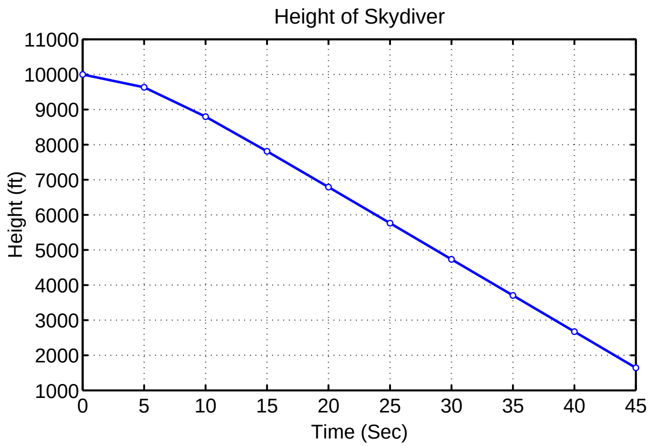
Skip Example

Example – Sky Diving 2

- Graph the Height *vs.* Time
- Compute the approximate velocity using the successive rows of the table
- Graph the velocity curve
- What is the approximate velocity in miles per hour at 30 seconds into the fall?
- Can you estimate when the sky diver would hit the ground if the parachute failed to open?

Example – Sky Diving

Solution: Graph the Height *vs.* Time



Example – Sky Diving

Solution: Compute the first two velocity points of the graph:

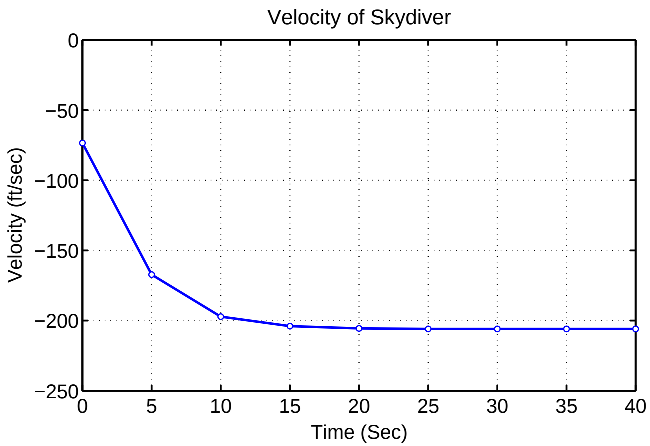
$$\begin{aligned} v(t_0) &= \frac{h(t_1)-h(t_0)}{t_1-t_0} = \frac{9,633-10,000}{5-0} = -73.4 \text{ ft/sec}, \\ v(t_1) &= \frac{h(t_2)-h(t_1)}{t_2-t_1} = \frac{8,797-9,633}{10-5} = -167.2 \text{ ft/sec}. \end{aligned}$$

The velocity at 30 seconds is

$$v(t_6) = \frac{3703-4733}{35-30} = -206 \text{ ft/sec},$$

Example – Sky Diving

Solution: Graph the velocity curve using calculations above



Example – Sky Diving

Solution: The graph shows the velocity of the sky diver levels off shortly after 10 sec

The **terminal velocity** is approximately the velocity at 30 sec or $v_{term} = -206$ ft/sec (which is about -140.5 mph)

At 45 sec, the sky diver is at 1643 ft and traveling at v_{term}

We get, time = distance/v = $1643/206 = 8.0$ sec to cover the remaining 1643 ft

Hence, the sky diver would fall for about $45 + 8 = 53$ sec if the parachute failed