

Applied Numerical Methods for Civil Engineering

CGN 3405 - 0002

Mathematical Modeling & Engineering Problem Solving

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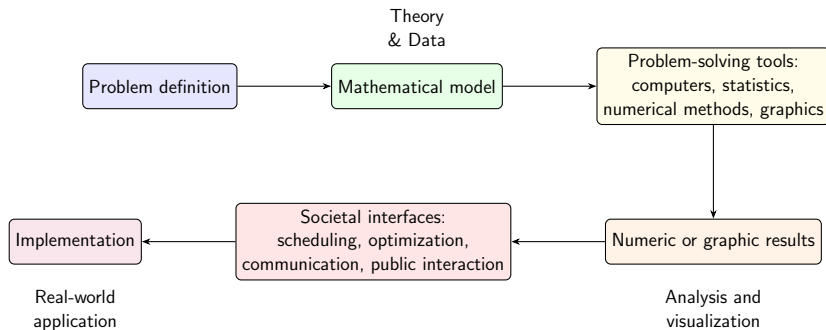
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How to understand

Applied Numerical Methods for Civil Engineering?

Numerical methods are techniques by which **mathematical problems** are formulated so that they can be solved with **arithmetic operations**.

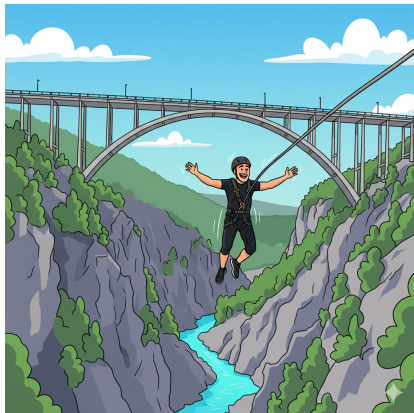
Engineering Problem Solving Process



Bungee Jumping

Engineering Task.

- A bungee jumping company needs to **predict velocity vs. time** during free-fall to design safe bungee cords.
- **Key Questions:**
 - What is the **maximum velocity** reached?
 - How long until maximum velocity?
 - What cord length is needed?



Physical Forces F_g and F_a

Two Main Forces: Physical Forces Acting on Jumper

$$F = F_g - F_a = m \cdot g - c_d \cdot v^2$$

- Gravity (Downward)

$$F_g = m \cdot g$$

with

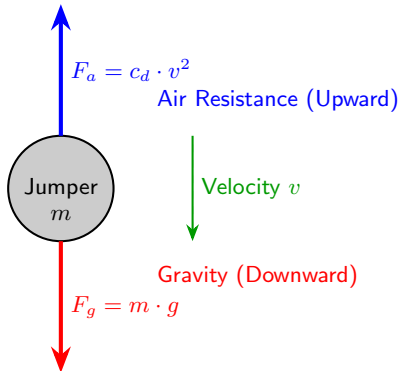
- m = mass (kg)
- $g = 9.81 \text{ m/s}^2$, gravitational acceleration

- Air Resistance (Upward)

$$F_a = c_d \cdot v^2$$

with

- c_d = drag coefficient (kg/m)
- v = velocity



Newton's Second Law

Mathematical Model - Newton's Second Law

- From $F = m \cdot a$:

$$F = m \frac{dv}{dt} = m \cdot g - c_d \cdot v^2$$

- Divide by m :

$$\frac{dv}{dt} = g - \frac{c_d}{m} v^2$$

Ordinary Differential Equation!!!

in terms of the differential rate of change in velocity.

- Initial condition:

$$v(0) = 0 \quad (\text{starts from rest})$$

- Problem definition:** Solve the velocity of the jumper in free fall as a function of time.
- Why Numerical Methods?**
 - Real engineering problems often **do not have simple analytical solutions!**

Euler's Method (Numerical)

Euler's Method - The Simplest Numerical Approach

- Essential idea:

Approximate continuous change with small discrete time steps Δt .

- Rewrite the formula of Bungee jumper velocity:

$$\begin{aligned}
 \underbrace{v_{t+\Delta t}}_{\text{new}} &= v_t + \Delta t \cdot \frac{dv_t}{dt} \\
 &= \underbrace{v_t}_{\text{old}} + \underbrace{\Delta t}_{\text{time step size}} \cdot \underbrace{\left(g - \frac{c_d}{m} v_t^2\right)}_{\text{acceleration}}
 \end{aligned}$$

from the ordinary differential equation:

$$\frac{dv}{dt} = g - \frac{c_d}{m} v^2$$

Euler's Method (Numerical)

Euler's Method - The Simplest Numerical Approach

- Formula of Bungee jumper velocity:

$$\underbrace{v_{t+\Delta t}}_{\text{new}} = \underbrace{v_t}_{\text{old}} + \underbrace{\Delta t}_{\text{time step size}} \cdot \underbrace{\left(g - \frac{c_d}{m} v_t^2\right)}_{\text{acceleration}}$$

- Computing **bungee jumper velocity** (step-by-step):

- Start at $t = 0$ and $v = 0$
- Compute **acceleration**:

$$a = g - \frac{c_d}{m} v_t^2$$

- Update **velocity**:

$$v_{t+\Delta t} = v_t + \Delta t \cdot a$$

- Increment time: $t = t + \Delta t$
- Repeat!

A Real Case

Input. Mass $m = 50$ kg, drag coefficient $c_d = 0.25$, and initial velocity $v_0 = 0$.
(Given $\Delta t = 1$ s)

Output. Bungee jumper velocity v_t .

- At time $t = 1$:

$$a = g - \frac{c_d}{m} v_0^2 = 9.81 - 0.005 \times 0^2 = 9.81$$

$$v_1 = v_0 + \Delta t \cdot a = 0 + 9.81 = \mathbf{9.81}$$

- At time $t = 2$:

$$a = g - \frac{c_d}{m} v_1^2 = 9.81 - 0.005 \times 9.81^2 = 9.33$$

$$v_2 = v_1 + \Delta t \cdot a = 9.81 + 1 \times 9.33 = \mathbf{19.14}$$

- At time $t = 3$

$$a = g - \frac{c_d}{m} v_2^2 = 9.81 - 0.005 \times 19.14^2 = 7.98$$

$$v_3 = v_2 + \Delta t \cdot a = 19.14 + 1 \times 7.98 = \mathbf{27.12}$$

- ...

The Basic Syntax of a for Loop in Python

Description.

- A **for** loop in Python is a control flow statement used to iterate over items of any sequence (such as a list, tuple, string, set, or dictionary) in the order that they appear.
- It is primarily used when you need to execute a block of code a specific, predetermined number of times or for each item in a collection.

The Basic Syntax of a for Loop in Python

Fibonacci Sequence.

- Definition: Given $f(1) = f(2) = 1$, the Fibonacci sequence takes the form of

$$f(n) = f(n-1) + f(n-2), n > 2$$

- Write down $f(3)$, $f(4)$, $f(5)$, $f(6)$, $f(7)$, \dots by yourself?

The Basic Syntax of a for Loop in Python

Fibonacci Sequence.

- Definition: Given $f(1) = f(2) = 1$, the Fibonacci sequence takes the form of

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- Write down $f(3)$, $f(4)$, $f(5)$, $f(6)$, $f(7)$, \dots by yourself?

$$f(3) = f(2) + f(1) = 2$$

$$f(4) = f(3) + f(2) = 3$$

$$f(5) = f(4) + f(3) = 5$$

$$f(6) = f(5) + f(4) = 8$$

$$f(7) = f(6) + f(5) = 13$$

- Python programming

```
1 import numpy as np
2
3 def fib(n):          # Input n>2
4     f = np.zeros(n)
5     f[0] = 1
6     f[1] = 1
7     for i in range(2, n):
8         f[i] = f[i - 1] + f[i - 2]
9     return f[n - 1]
```

Python Programming for Euler's Method

- **Python programming example.** Computing **bungee jumper velocity**:
 - Start at $t = 0$ and $v = 0$
 - Compute **acceleration**:

$$a = g - \frac{c_d}{m} v_t^2$$

- Update **velocity**:

$$v_{t+\Delta t} = v_t + \Delta t \cdot a$$

- Increment time: $t = t + \Delta t$
- Repeat!

```
1 import numpy as np
2
3 def euler(m, g, cd, v0, delta_t, time_steps):
4     v = np.zeros(time_steps)           # Velocity
5     v[0] = v0                          # Initial velocity
6     for i in range(time_steps - 1):    # Repeat
7         a = g - cd / m * (v[i] ** 2)   # Acceleration
8         v[i + 1] = v[i] + delta_t * a  # Velocity
9     return v
```

A Real Case

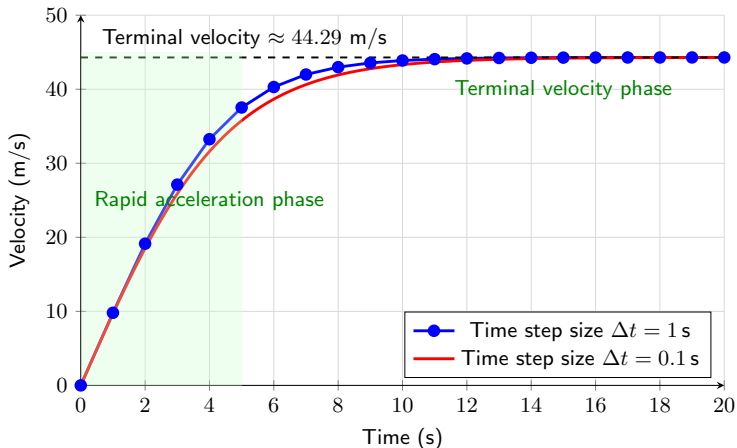
- Mass: $m = 50$ kg
- Gravitational acceleration: $g = 9.81$ m/s²
- Drag coefficient: $c_d = 0.25$

```
1 import numpy as np
2
3 # Parameters
4 m = 50                # Mass (kg)
5 g = 9.81              # Gravity (m/s^2)
6 cd = 0.25            # Drag coefficient
7 v0 = 0               # Initial velocity
8
9 # Time setup
10 delta_t = 1          # Time step size
11 t_end = 20           # Total time
12 time_steps = int(t_end / delta_t) + 1
13
14 # Euler's method
15 t = np.linspace(0, t_end, time_steps)
16 v = euler(m, g, cd, v0, delta_t, time_steps)
```

Velocity vs. Time

Bungee jumper **velocity vs. time** (w/ air resistance)

- Comparison between $\Delta t = 1$ s and $\Delta t = 0.1$ s



Velocity vs. Time

Terminal velocity:

$$a = g - \frac{c_d}{m}v^2 = 0 \quad \Rightarrow \quad v = \sqrt{\frac{mg}{c_d}}$$

In this case:

$$v = \sqrt{\frac{mg}{c_d}} = \sqrt{\frac{50 \times 9.81}{0.25}} = 44.29 \text{ m/s}$$

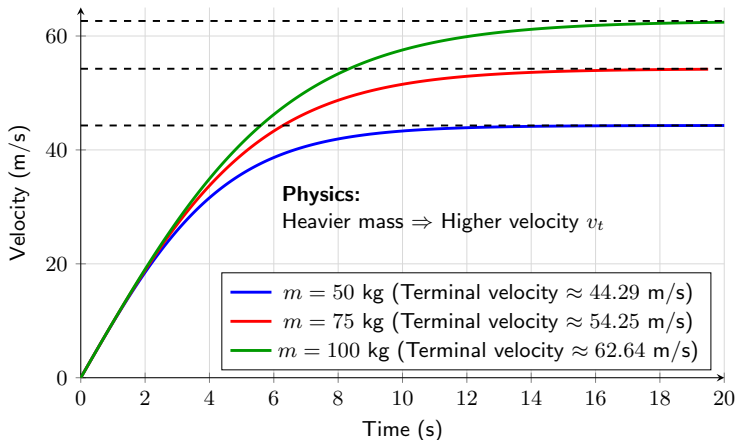
Numerical method insight.

- Demonstrates importance of time step selection in simulations
- Fine time steps give more accurate results
- Coarse time steps are faster to compute but less accurate

Velocity vs. Time (Different Mass)

Bungee jumper **velocity vs. time** (w/ air resistance)

- Comparison among mass $m = 50$ kg, 75 kg, 100 kg



Bungee Jumping

Bungee Jumping

Quizzes Now!

- **Today's participation:** Please check out

"Class Participation Quiz 3"

Time slot: **3:00PM – 3:30PM**

on Canvas.

- Online engagement (graded quizzes)

"Quiz 3" (14 questions)

Deadline: **11:59PM, January 21, 2026**

on Canvas.