

Estimating the largest Lyapunov exponent (LLE) for the Lorenz system (Assignment Sheet 9)

Introduction To Chaos Applied To Systems, Processes And Products (ETSIDI, UPM)

Alfonso Allen-Perkins, Juan Carlos Bueno and Eduardo Faleiro

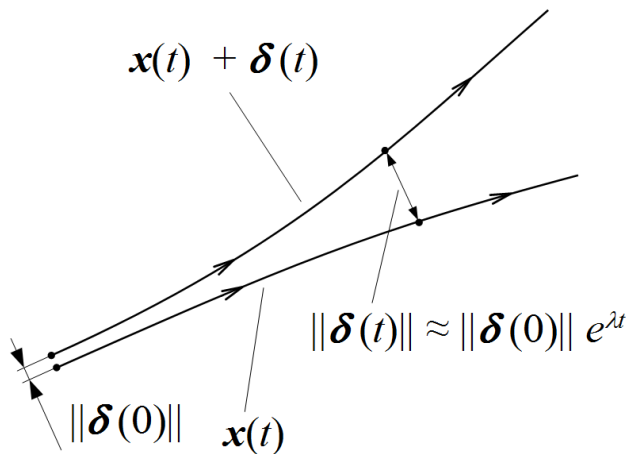
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Largest Lyapunov Exponent for 3D flows

The **Largest Lyapunov Exponent (LLE)** quantifies chaos by measuring sensitivity to initial conditions. Here, we'll estimate the LLE for the classical Lorenz attractor, a canonical chaotic system.



Source: Wikipedia – Lyapunov exponent

1. Load the required packages

```
library(ggplot2)
library(deSolve)
```

2. Define the Lorenz system

The Lorenz system is defined by:

$$\begin{aligned}\dot{x} &= \sigma \cdot (y - x) \\ \dot{y} &= x \cdot (\rho - z) - y \\ \dot{z} &= x \cdot y - \beta \cdot z\end{aligned}$$

Lorenz originally used the values $\sigma = 10$, $\rho = 28$, and $\beta = 8/3$, under which the system exhibits chaotic behavior.

```
lorenz <- function(t, state, parameters) {
  with(as.list(c(state, parameters)), {
    dx <- sigma * (y - x)
    dy <- x * (rho - z) - y
    dz <- x * y - beta * z
    list(c(dx, dy, dz))
  })
}
```

3. Start with any initial condition in the basin of attraction and iterate until the orbit is on the attractor.

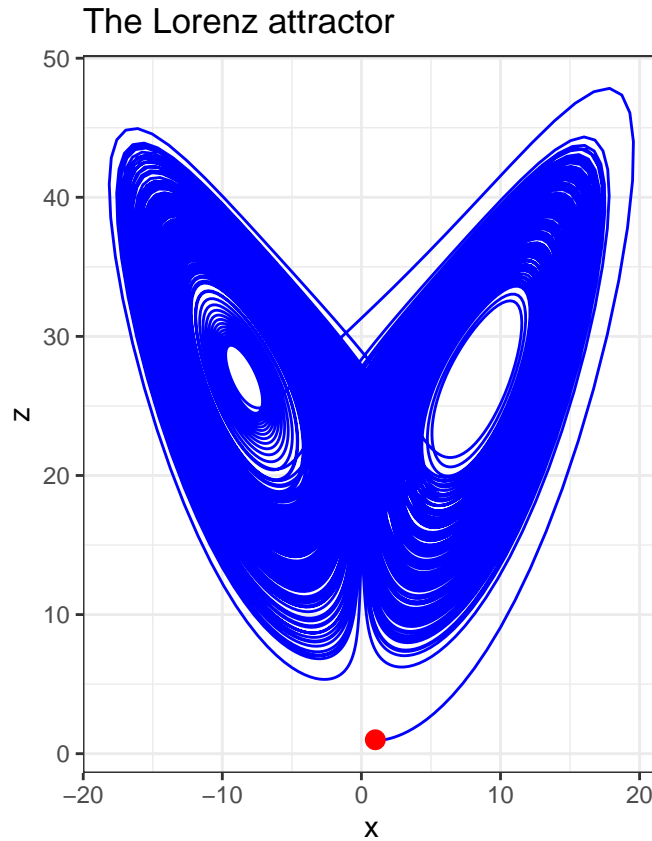
```
# Parameters
parms <- c(sigma = 10, rho = 28, beta = 8/3)

# Initial conditions and integration settings
state_aux <- c(x = 1, y = 1, z = 1)
dt <- 0.01
total_time <- 200
times <- seq(0, total_time, by = dt)

# Integrate to reach attractor
orbit_aux <- ode(state_aux, times, lorenz, parms, method = "ode45")
orbit_aux_df <- as.data.frame(orbit_aux)
```

4. Visualize the Lorenz attractor

```
ggplot()+
  geom_path(data = orbit_aux_df,
    aes(x = x, y = z), color = "blue")+
  geom_point(data = data.frame(x=state_aux["x"],y=state_aux["y"],z=state_aux["z"]),
    aes(x = x, y = z), color = "red", size = 3)+
  labs(title = "The Lorenz attractor")+
  coord_fixed()+
  theme_bw()
```



5. Select the last point of the previous orbit. It should be in the attractor.

```
# Select final state
state <- orbit_aux[nrow(orbit_aux),c("x", "y", "z")]
```

6. Select a nearby point (separated by δ_0).

```
# Define initial nearby point separated by small d0
d0 <- 1e-8
state_perturbed <- state + c(d0, 0, 0)
```

7. Advance both orbits one iteration and calculate new separation δ_1 .

```
# Advance both states by one iteration (time step dt)
orbit1 <- ode(state, c(0, dt), lorenz, parms, method = "ode45")[2,-1]
orbit2 <- ode(state_perturbed, c(0, dt), lorenz, parms, method = "ode45")[2,-1]

# Calculate new separation d1
d1_vector <- orbit2 - orbit1
d1 <- sqrt(sum(d1_vector^2))
```

8. Evaluate $\log|\delta_1/\delta_0|$ in any convenient base.

```
# Evaluate log(d1/d0)
log(d1/d0)
```

```
## [1] -0.0870614
```

9. Readjust one orbit so its separation is δ_0 in same direction as δ_1 .

```
# Readjust perturbed orbit to separation d0
state <- orbit1
state_perturbed <- orbit1 + (d0 / d1) * d1_vector
```

10. We use a for loop to repeat the previous 3 steps and obtain new values of $\log|\delta_1/\delta_0|$.

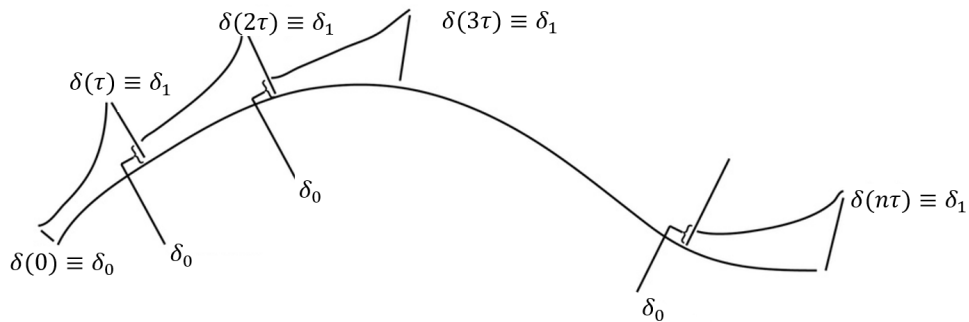


Figure 1: Numerical calculation of the LLE

Source: Numerical calculation of the largest Lyapunov exponent

11. the largest Lyapunov exponent is the average value of $\lambda_1 = \langle \log|\delta_1/\delta_0| \rangle$.

```
# Parameters for Lyapunov exponent calculation
n_iter <- 1e4
lyapunov_sum <- 0

# Loop to calculate Lyapunov exponent
for (i in 1:n_iter) {

  # Advance both states by one iteration (time step dt)
  orbit1 <- ode(state, c(0, dt), lorenz, parms, method = "ode45")[2,-1]
  orbit2 <- ode(state_perturbed, c(0, dt), lorenz, parms, method = "ode45")[2,-1]

  # Calculate new separation d1
  d1_vector <- orbit2 - orbit1
  d1 <- sqrt(sum(d1_vector^2))

  # Evaluate log(d1/d0)
  lyapunov_sum <- lyapunov_sum + log(d1/d0)

  # Readjust perturbed orbit to separation d0
```

```

state <- orbit1
state_perturbed <- orbit1 + (d0 / d1) * d1_vector
}

# Calculate largest Lyapunov exponent
l1 <- lyapunov_sum / (n_iter * dt)

# Print the result
cat("Largest Lyapunov exponent:", l1, "\n")

```

```
## Largest Lyapunov exponent: 0.9099768
```

Interpretation

- **Positive LLE:** Indicates sensitive dependence on initial conditions and exponential divergence of trajectories (chaos).
- **Larger LLE:** Suggests more sensitive dependence on initial conditions.

```

if (l1 > 0) {
  cat("The system shows chaotic behavior.\n")
} else {
  cat("The system does not show chaotic behavior.\n")
}

```

```
## The system shows chaotic behavior.
```

Further exploration

Try varying the initial conditions and parameters (σ , ρ , β) to explore different dynamical regimes. For instance, estimate the largest Lyapunov exponent of the Lorenz system under the following parameter set: $\sigma = 10$, $\rho = 350$, $\beta = 8/3$