Optimal Supply Networks I: Branching

Last updated: 2021/10/06, 23:35:55 EDT

Principles of Complex Systems, Vols. 1 & 2
CSYS/MATH 300 and 303, 2021–2022 | @pocsvox

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Outline

Optimal supply networks

What's the best way to distribute stuff?

- Stuff = medical services, energy, people, ...
- Some fundamental network problems:
  1. Distribute stuff from a single source to many sinks
  2. Distribute stuff from many sources to many sinks
  3. Redistribute stuff between nodes that are both sources and sinks
- Supply and Collection are equivalent problems

Single source optimal supply

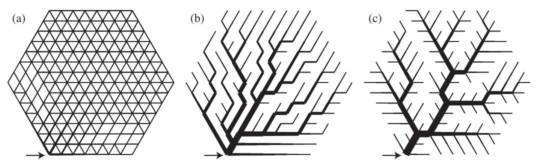
Basic question for distribution/supply networks:

- How does flow behave given cost:

$$C = \sum_j I_j^\gamma Z_j$$

where
I_j = current on link j
and
Z_j = link j's impedance?
- Example: $\gamma = 2$ for electrical networks.

Single source optimal supply

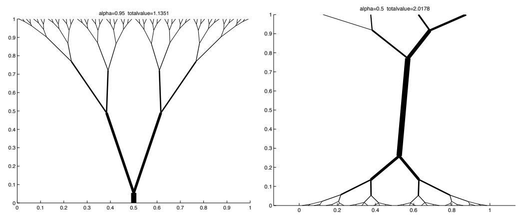


(a) $\gamma > 1$: Braided (bulk) flow
(b) $\gamma < 1$: Local minimum: Branching flow
(c) $\gamma < 1$: Global minimum: Branching flow
- Note: This is a single source supplying a region.

From Bohn and Magnasco [3]
See also Banavar *et al.* [1]: "Topology of the Fittest Transportation Network"; focus is on presence or absence of loops—same story

Single source optimal supply

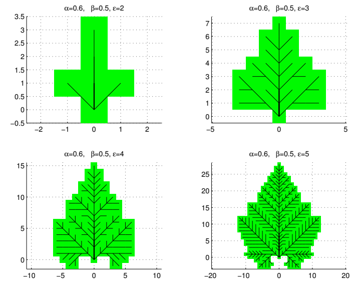
Optimal paths related to transport (Monge) problems:



"Optimal paths related to transport problems"
Qinglan Xia,
Communications in Contemporary Mathematics, **5**, 251–279, 2003. [19]

Growing networks—two parameter model: [20]

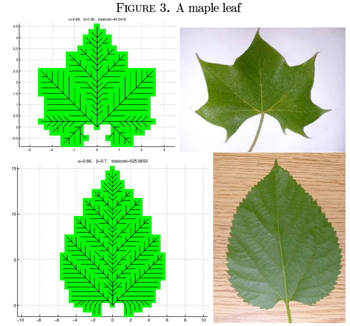
FIGURE 1. $\alpha = 0.6, \beta = 0.5$



- Parameters control impedance ($0 \le \alpha < 1$) and angles of junctions ($0 < \beta$)
- For this example: $\alpha = 0.6$ and $\beta = 0.5$

Growing networks: [20]

FIGURE 3. A maple leaf



- Top: $\alpha = 0.66$, $\beta = 0.38$; Bottom: $\alpha = 0.66$, $\beta = 0.70$

Single source optimal supply

An immensely controversial issue ...

- The form of natural branching networks: Random, optimal, or some combination? [6, 18, 2, 5, 4]
- River networks, blood networks, trees, ...

Two observations:

- Self-similar networks appear everywhere in nature for single source supply/single sink collection.
- Real networks differ in details of scaling but reasonably agree in scaling relations.

River network models

Optimality:

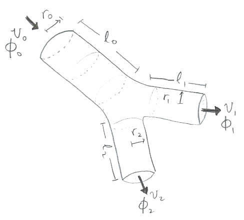
- Optimal channel networks [13]
- Thermodynamic analogy [14]

versus ...

Randomness:

- Scheidegger's directed random networks
- Undirected random networks

Optimization—Murray's law



- Murray's law (1926) connects branch radii at forks: [11, 10, 12, 7, 16]

$$r_0^3 = r_1^3 + r_2^3$$

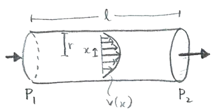
where r_0 = radius of main branch, and r_1 and r_2 are radii of sub-branches.

- Holds up well for outer branchings of blood networks.
- Also found to hold for trees [12, 8] when xylem is not a supporting structure [9].
- See D'Arcy Thompson's "On Growth and Form" for background and general inspiration [15, 16].

- Use hydraulic equivalent of Ohm's law:

$$\Delta p = \Phi Z \Leftrightarrow V = IR$$

where Δp = pressure difference, Φ = flux.



- Fluid mechanics: Poiseuille impedance for smooth Poiseuille flow in a tube of radius r and length ℓ:

$$Z = \frac{8\eta\ell}{\pi r^4}$$

- η = dynamic viscosity (units: $ML^{-1}T^{-1}$).
- Power required to overcome impedance:

$$P_{\text{drag}} = \Phi \Delta p = \Phi^2 Z.$$

- Also have rate of energy expenditure in maintaining blood given metabolic constant c:

$$P_{\text{metabolic}} = c r^2 \ell$$

Optimization—Murray's law

Aside on P_{drag}

- Work done = $F \cdot d$ = energy transferred by force F
- Power = P = rate work is done = $F \cdot v$
- Δp = Force per unit area
- Φ = Volume per unit time
  = cross-sectional area · velocity
- So $\Phi \Delta p$ = Force · velocity

Optimization—Murray's law

Murray's law:

- Total power (cost):

$$P = P_{\text{drag}} + P_{\text{metabolic}} = \Phi^2 \frac{8\eta\ell}{\pi r^4} + c r^2 \ell$$

- Observe power increases linearly with ℓ
- But r's effect is nonlinear:
  - increasing r makes flow easier but increases metabolic cost (as r^2)
  - decreasing r decrease metabolic cost but impedance goes up (as r^{-4})

Optimization—Murray's law

Murray's law:

- Minimize P with respect to r:

$$\frac{\partial P}{\partial r} = \frac{\partial}{\partial r}\left(\Phi^2 \frac{8\eta\ell}{\pi r^4} + c r^2 \ell\right)$$

$$= -4\Phi^2 \frac{8\eta\ell}{\pi r^5} + c2r\ell = 0$$

- Rearrange/cancel/slap:

$$\Phi^2 = \frac{c\pi r^6}{16\eta} = k^2 r^6$$

where k = constant.

Optimization—Murray's law

Murray's law:

- So we now have:

$$\Phi = k r^3$$

- Flow rates at each branching have to add up (else our organism is in serious trouble ...):

$$\Phi_0 = \Phi_1 + \Phi_2$$

where again 0 refers to the main branch and 1 and 2 refers to the offspring branches

- All of this means we have a groovy cube-law:

$$r_0^3 = r_1^3 + r_2^3$$

Optimization

Murray meets Tokunaga:

- Φ_ω = volume rate of flow into an order ω vessel segment
- Tokunaga picture:

$$\Phi_\omega = 2\Phi_{\omega-1} + \sum_{k=1}^{\omega-1} T_k \Phi_{\omega-k}$$

- Using $\phi_\omega = k r_\omega^3$

$$r_\omega^3 = 2 r_{\omega-1}^3 + \sum_{k=1}^{\omega-1} T_k r_{\omega-k}^3$$

- Find Horton ratio for vessel radius $R_r = r_\omega / r_{\omega-1}$ ...

Optimization

Murray meets Tokunaga:

- Find R_r^3 satisfies same equation as R_n and R_v (v is for volume):

$$R_r^3 = R_n = R_v$$

- Is there more we could do here to constrain the Horton ratios and Tokunaga constants?

Optimization

Murray meets Tokunaga:

- Isometry: $V_\omega \propto \ell_\omega^3$
- Gives

$$R_\ell^3 = R_r^3 = R_n = R_v$$

- We need one more constraint ...
- West *et al.* (1997) [18] achieve similar results following Horton's laws (but this work is disaster).
- So does Turcotte *et al.* (1998) [17] using Tokunaga (sort of).

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