Optimal Supply Networks I: Branching

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Principles of Complex Systems, Vols. 1, 2, & 3D
CSYS/MATH 6701, 6713, & a pretend number, 2024–2025

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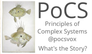
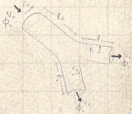
Computational Story Lab | Vermont Complex Systems Center
Santa Fe Institute | University of Vermont





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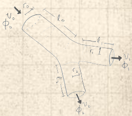

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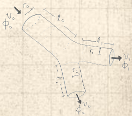
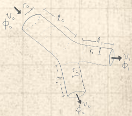


Outline

Optimal transportation

Optimal branching
- Murray's law
- Murray meets Tokunaga

References



Optimal supply networks

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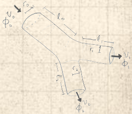

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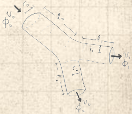

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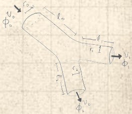

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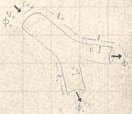

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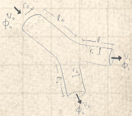

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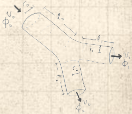
- Supply and Collection are equivalent problems

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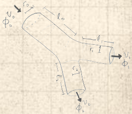
Single source optimal supply

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.



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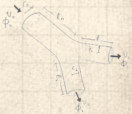
- Example: $\gamma = 2$ for electrical networks.



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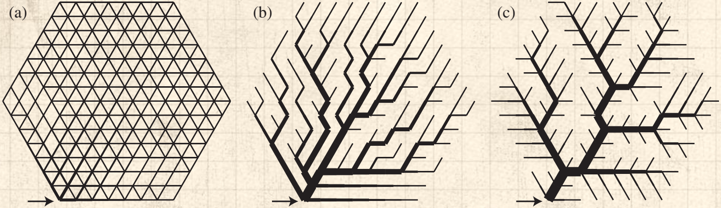
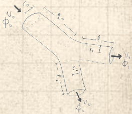


(a) $\gamma > 1$: Braided (bulk) flow
(b) $\gamma < 1$: Local minimum: Branching flow
(c) $\gamma < 1$: Global minimum: Branching flow

- 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



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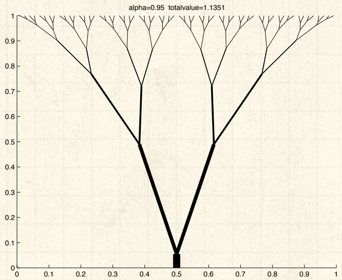
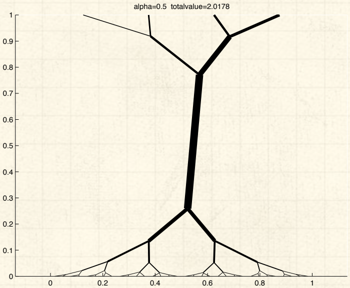
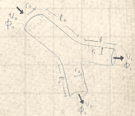
Optimal paths related to transport (Monge) problems:



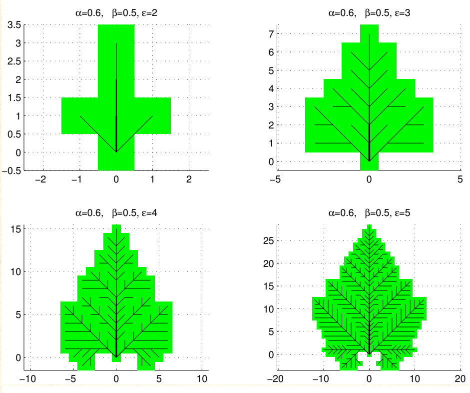


"Optimal paths related to transport problems"
Qinglan Xia,
Communications in Contemporary Mathematics, **5**, 251–279, 2003. [20]

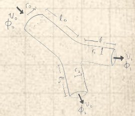


Growing networks—two parameter model: [21]

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

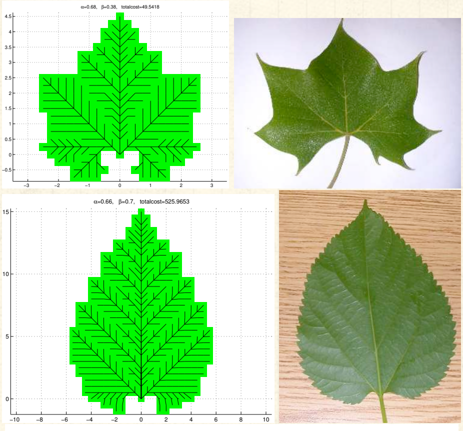


- Parameters control impedance ($0 \leq \alpha < 1$) and angles of junctions ($0 < \beta$)
- For this example: $\alpha = 0.6$ and $\beta = 0.5$

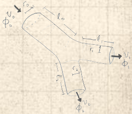


Growing networks: [21]

FIGURE 3. A maple leaf



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



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An immensely controversial issue ...

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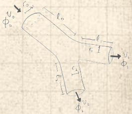

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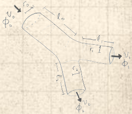

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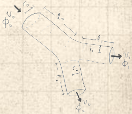

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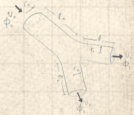
- Real networks differ in details of scaling but reasonably agree in scaling relations.



River network models

Optimality:

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

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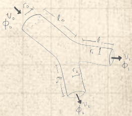
versus ...

Randomness:

- Scheidegger's directed random networks
- Undirected random networks

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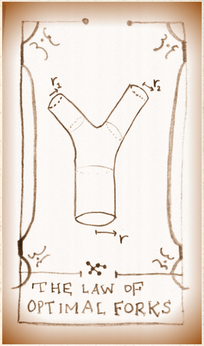
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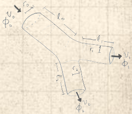
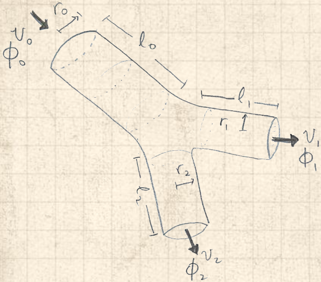
THE LAW OF OPTIMAL FORKS

Outline



Optimization—Murray's law



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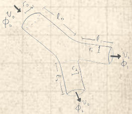
$$r_{\text{parent}}^3 = r_{\text{offspring1}}^3 + r_{\text{offspring2}}^3$$

where r_{parent} = radius of 'parent' branch, and $r_{\text{offspring1}}$ and $r_{\text{offspring2}}$ are radii of the two 'offspring' sub-branches.



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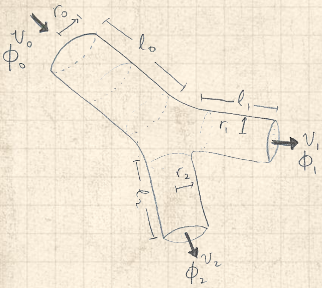

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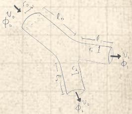

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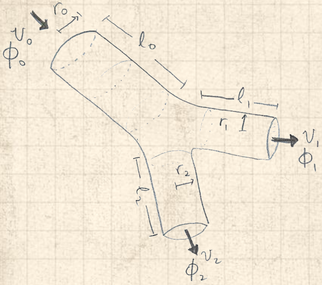

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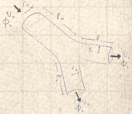

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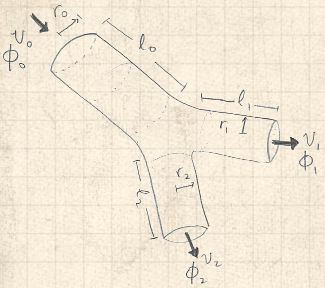

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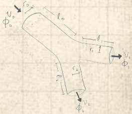
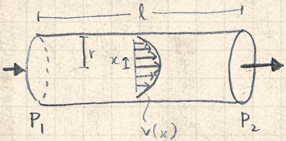
- Also found to hold for trees [12, 8] when xylem is not a supporting structure [9].
- See D'Arcy Thompson's "On Growth and Form" for background and general inspiration [16, 17].

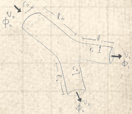


Use hydraulic equivalent of Ohm's law:

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

where Δp = pressure difference, Φ = flux.





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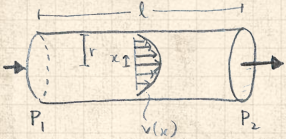
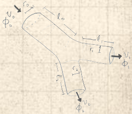


- Fluid mechanics: Poiseuille impedance for smooth Poiseuille flow in a tube of radius r and length ℓ:

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

- η = dynamic viscosity (units: $ML^{-1}T^{-1}$).



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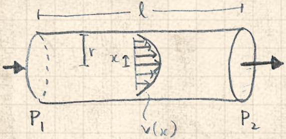
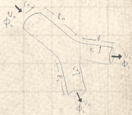


- Fluid mechanics: Poiseuille impedance for smooth Poiseuille flow in a tube of radius r and length ℓ:

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

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

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



- Use hydraulic equivalent of Ohm's law:

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

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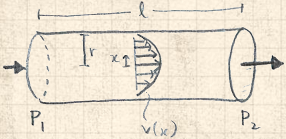

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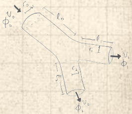
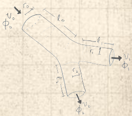
- Also have rate of energy expenditure in maintaining blood given metabolic constant c:

$$P_{\text{metabolic}} = cr^2\ell$$



Optimization—Murray's law

Aside on P_{drag}



Optimization—Murray's law

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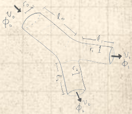

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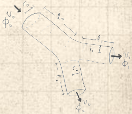

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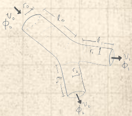

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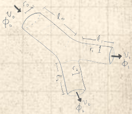
- Φ = Volume flow per unit time (current)
  = cross-sectional area · velocity



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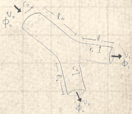
- So $\Phi \Delta p$ = Force · velocity

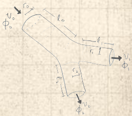


Optimization—Murray's law

Murray's law:

- Total power (cost):

$$P = P_{\text{drag}} + P_{\text{metabolic}}$$



Optimization—Murray's law

Murray's law:

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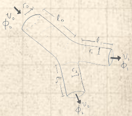
$$P = P_{\text{drag}} + P_{\text{metabolic}} = \Phi^2 \frac{8\eta\ell}{\pi r^4} + c r^2 \ell$$



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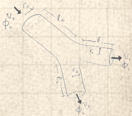
- Observe power increases linearly with ℓ



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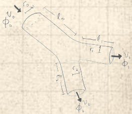
- But r's effect is nonlinear:



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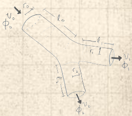

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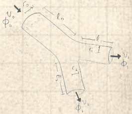
- Observe power increases linearly with ℓ
- But r's effect is nonlinear:
  - increasing r makes flow easier but increases metabolic cost (as r^2)
  - decreasing r decrease metabolic cost but impedance goes up (as r^{-4})

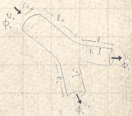


Optimization—Murray's law

Murray's law:

- Minimize P with respect to r:

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



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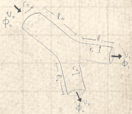
- Flow rates at each branching have to add up (else our organism is in serious trouble ...):

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

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

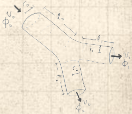


Optimization—Murray's law

Murray's law:

- Find:

$$\Phi = kr^3$$



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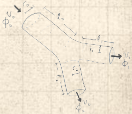


Optimization—Murray's law

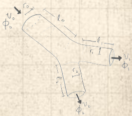
Murray's law:

- Find:

$$\Phi = kr^3$$

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

$$\boxed{r_{\text{parent}}^3 = r_{\text{offspring1}}^3 + r_{\text{offspring2}}^3}$$



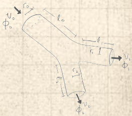
Outline

Optimal transportation

Optimal branching

- Murray's law
- Murray meets Tokunaga

References



Murray meets Tokunaga:

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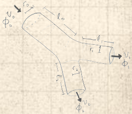
- Tokunaga picture:

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



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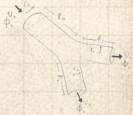
- Using $\phi_\omega = k r_\omega^3$

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



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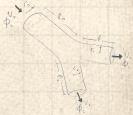
- Using $\phi_\omega = k r_\omega^3$

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

- Same form as:

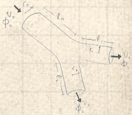
$$n_\omega = \underbrace{2 n_{\omega+1}}_{\text{generation}} + \sum_{\omega'=\omega+1}^{\Omega} \underbrace{T_{\omega'-\omega} n_{\omega'}}_{\text{absorption}}$$



Optimization

Murray meets Tokunaga:

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



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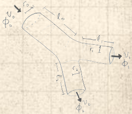

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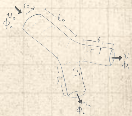
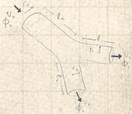
- Is there more we could do here to constrain the Horton ratios and Tokunaga constants?



Optimization

Murray meets Tokunaga:

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



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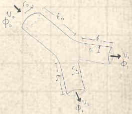
$$R_\ell^3 = R_r^3 = R_n = R_v$$



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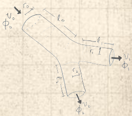
- We need one more constraint ...



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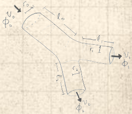
- West *et al.* (1997) [19] achieve similar results following Horton's laws (but this work is a disaster).



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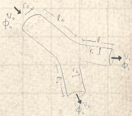
- We need one more constraint ...
- West *et al.* (1997) [19] achieve similar results following Horton's laws (but this work is a disaster).
- So does Turcotte *et al.* (1998) [18] using Tokunaga (sort of).



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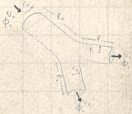

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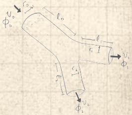

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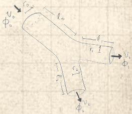

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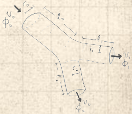

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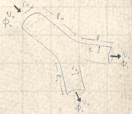

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