

Optimal Supply Networks III: Redistribution

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Principles of Complex Systems,
Vols. 1, 2, 3D, 4 Fourever, V for Vendetta

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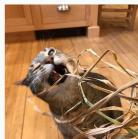
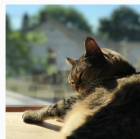
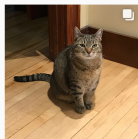
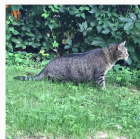
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Many sources, many sinks

How do we distribute sources?

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Many sources, many sinks

How do we distribute sources?



Focus on 2-d (results generalize to higher dimensions).

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Many sources, many sinks

How do we distribute sources?



Focus on 2-d (results generalize to higher dimensions).



Sources = hospitals, post offices, pubs, ...

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Many sources, many sinks

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How do we distribute sources?



Focus on 2-d (results generalize to higher dimensions).



Sources = hospitals, post offices, pubs, ...



Key problem: How do we cope with uneven population densities?



Many sources, many sinks

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How do we distribute sources?

- Focus on 2-d (results generalize to higher dimensions).
- Sources = hospitals, post offices, pubs, ...
- Key problem:** How do we cope with uneven population densities?
- Obvious: if density is uniform then sources are best distributed **uniformly**.



Many sources, many sinks

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- Which lattice is optimal?



Many sources, many sinks

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How do we distribute sources?

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- Which lattice is optimal? The **hexagonal lattice**
- Q2:** Given population density is uneven, what do we do?



Many sources, many sinks

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How do we distribute sources?

- Focus on 2-d (results generalize to higher dimensions).
- Sources = hospitals, post offices, pubs, ...
- Key problem:** How do we cope with uneven population densities?
- Obvious: if density is uniform then sources are best distributed **uniformly**.
- Which lattice is optimal? The **hexagonal lattice**
- Q2:** Given population density is uneven, what do we do?
- We'll follow work by Stephan (1977, 1984) ^[4, 5], Gastner and Newman (2006) ^[2], Um *et al.* (2009) ^[6], and work cited by them.



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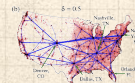
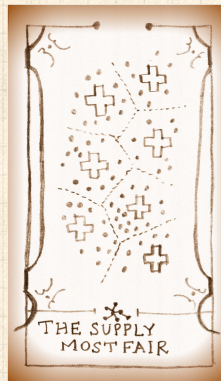
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Optimal source allocation: Size-density law¹

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Solidifying the basic problem

¹Looks good for not naming maps after mappers. But then we find out that the original discovery was by Prof. Quimbleton St. John Size IV and his graduate student Horace B. Density.



Optimal source allocation: Size-density law¹

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Solidifying the basic problem



Given a region with some population distribution ρ , most likely uneven.

¹Looks good for not naming maps after mappers. But then we find out that the original discovery was by Prof. Quimbleton St. John Size IV and his graduate student Horace B. Density.



Optimal source allocation: Size-density law¹

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Solidifying the basic problem

- Given a region with some population distribution ρ , most likely uneven.
- Given resources to build and maintain N facilities.
- Q:** How do we locate these N facilities so as to **minimize the average distance** between an **individual's residence** and the **nearest facility**?

¹Looks good for not naming maps after mappers. But then we find out that the original discovery was by Prof. Quimbleton St. John Size IV and his graduate student Horace B. Density.





“Optimal design of spatial distribution networks”

Gastner and Newman,
Phys. Rev. E, **74**, 016117, 2006. [2]

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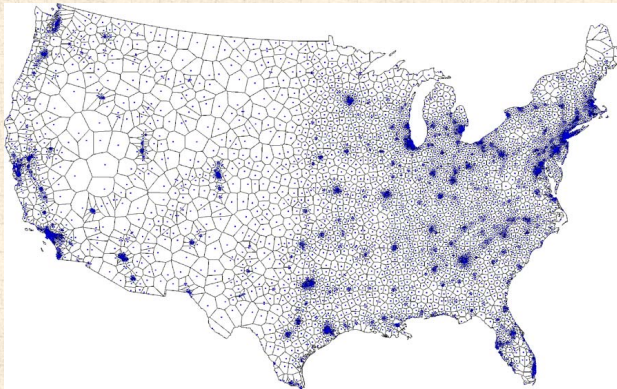
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-  Approximately optimal location of 5000 facilities.
-  Based on 2000 Census data.
-  Simulated annealing + Voronoi tessellation.



Optimal source allocation

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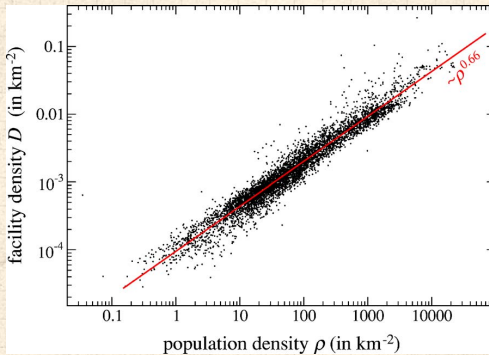
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Optimal facility density ρ_{fac} vs. population density ρ_{pop} .



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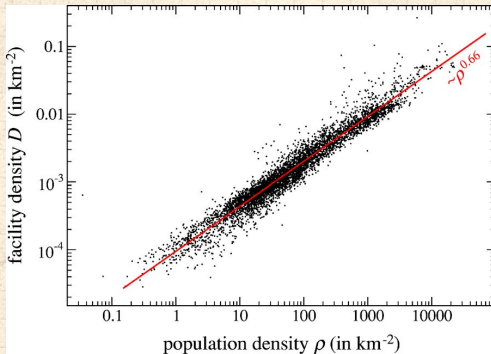
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 Optimal facility density ρ_{fac} vs. population density ρ_{pop} .

 Fit is $\rho_{\text{fac}} \propto \rho_{\text{pop}}^{0.66}$ with $r^2 = 0.94$.



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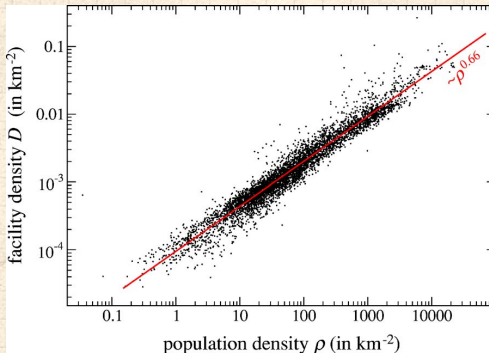
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 Optimal facility density ρ_{fac} vs. population density ρ_{pop} .

 Fit is $\rho_{\text{fac}} \propto \rho_{\text{pop}}^{0.66}$ with $r^2 = 0.94$.

 Looking good for a 2/3 power ...



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$$\rho_{\text{fac}} \propto \rho_{\text{pop}}^{2/3}$$



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Why?



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Size-density law:



$$\rho_{\text{fac}} \propto \rho_{\text{pop}}^{2/3}$$



Why?



Again: Different story to branching networks where there was either one source or one sink.



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Size-density law:



$$\rho_{\text{fac}} \propto \rho_{\text{pop}}^{2/3}$$



Why?



Again: Different story to branching networks where there was either one source or one sink.



Now sources & sinks are distributed throughout region.



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“Territorial division: The least-time constraint
behind the formation of subnational boundaries” 

G. Edward Stephan,
Science, **196**, 523–524, 1977. ^[4]



We first examine Stephan’s treatment (1977) ^[4, 5]





“Territorial division: The least-time constraint
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Zipf-like approach: invokes **principle of minimal effort**.



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“Territorial division: The least-time constraint
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We first examine Stephan’s treatment (1977) ^[4, 5]



Zipf-like approach: invokes **principle of minimal effort**.



Also known as the Homer Simpson principle.



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Optimal source allocation

- Consider a region of area A and population P with a single functional center that everyone needs to access every day.
- Build up a general cost function based on time expended to **access and maintain center**.

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- 

Optimal source allocation

- Consider a region of area A and population P with a single functional center that everyone needs to access every day.
- Build up a general cost function based on time expended to **access and maintain center**.
- Write **average travel distance** to center as $\langle d \rangle$ and assume **average speed of travel** is $\langle v \rangle$.
- Assume **isometry**: average travel distance $\langle d \rangle$ will be on the length scale of the region which is $\sim A^{1/2}$



Optimal source allocation

- Consider a region of area A and population P with a single functional center that everyone needs to access every day.
- Build up a general cost function based on time expended to **access and maintain center**.
- Write **average travel distance** to center as $\langle d \rangle$ and assume **average speed of travel** is $\langle v \rangle$.
- Assume **isometry**: average travel distance $\langle d \rangle$ will be on the length scale of the region which is $\sim A^{1/2}$
- Average time expended per person in accessing facility is therefore

$$\langle d \rangle / \langle v \rangle = c A^{1/2} / \langle v \rangle$$

where c is an unimportant shape factor.



Optimal source allocation

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Next assume facility requires regular maintenance (person-hours per day).



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Next assume facility requires regular maintenance (person-hours per day).



Call this quantity τ .



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Next assume facility requires regular maintenance (person-hours per day).



Call this quantity τ .



If burden of mainenance is shared then average cost per person is τ/P where P = population.



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- Next assume facility requires regular maintenance (person-hours per day).
- Call this quantity τ .
- If burden of maintenance is shared then average cost per person is τ/P where P = population.
- Replace P by $\rho_{\text{pop}} A$ where ρ_{pop} is density.



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-  Next assume facility requires regular maintenance (person-hours per day).
-  Call this quantity τ .
-  If burden of maintenance is shared then average cost per person is τ/P where P = population.
-  Replace P by $\rho_{\text{pop}} A$ where ρ_{pop} is density.
-  Important assumption: uniform density.



Optimal source allocation

- Next assume facility requires regular maintenance (person-hours per day).
- Call this quantity τ .
- If burden of maintenance is shared then average cost per person is τ/P where P = population.
- Replace P by $\rho_{\text{pop}}A$ where ρ_{pop} is density.
- Important assumption: uniform density.
- Total average time cost per person:

$$T = \langle d \rangle / \langle v \rangle + \tau / (\rho_{\text{pop}}A) = cA^{1/2} / \langle v \rangle + \tau / (\rho_{\text{pop}}A).$$



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- $$T = \langle d \rangle / \langle v \rangle + \tau / (\rho_{\text{pop}} A) = c A^{1/2} / \langle v \rangle + \tau / (\rho_{\text{pop}} A).$$

-

Optimal source allocation



Differentiating ...

$$\frac{\partial T}{\partial A} = \frac{\partial}{\partial A} \left(cA^{1/2} / \langle v \rangle + \tau / (\rho_{\text{pop}} A) \right)$$

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Optimal source allocation



Differentiating ...

$$\begin{aligned}\frac{\partial T}{\partial A} &= \frac{\partial}{\partial A} \left(cA^{1/2} / \langle v \rangle + \tau / (\rho_{\text{pop}} A) \right) \\ &= \frac{c}{2 \langle v \rangle A^{1/2}} - \frac{\tau}{\rho_{\text{pop}} A^2}\end{aligned}$$

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Optimal source allocation



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Rearrange:

$$A = \left(\frac{2 \langle v \rangle \tau}{c \rho_{\text{pop}}} \right)^{2/3}$$

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Optimal source allocation



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Optimal source allocation



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facilities per unit area ρ_{fac} :

$$\rho_{\text{fac}} \propto A^{-1} \propto \rho_{\text{pop}}^{2/3}$$



Optimal source allocation



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facilities per unit area ρ_{fac} :

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Groovy ...



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An issue:

🧱 Maintenance (τ) is assumed to be **independent** of population and area (P and A)

🧱 Stephan's online book
"The Division of Territory in Society" is here .

🧱 (It used to be here .)

🧱 The Readme  is well worth reading (1995).



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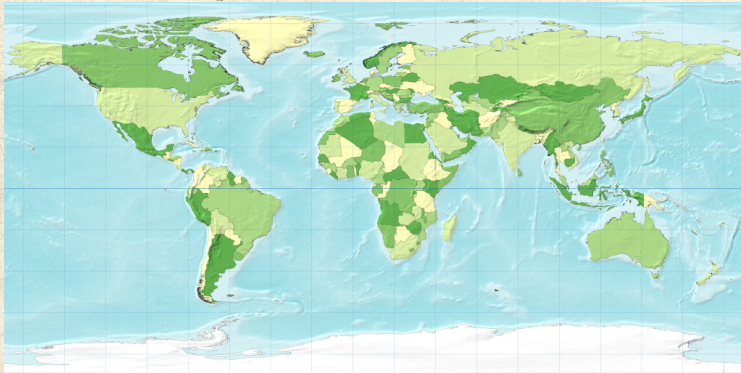
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Standard world map:



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Cartogram of countries 'rescaled' by population:



Cartograms

Diffusion-based cartograms:

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Cartograms

Diffusion-based cartograms:



Idea of cartograms is to **distort areas** to more accurately represent some local density ρ_{pop} (e.g. population).

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Cartograms

Diffusion-based cartograms:

- ❏ Idea of cartograms is to **distort areas** to more accurately represent some local density ρ_{pop} (e.g. population).
- ❏ Many methods put forward—typically involve some kind of physical analogy to **spreading or repulsion**.
- ❏ Algorithm due to Gastner and Newman (2004) ^[1] is based on **standard diffusion**:

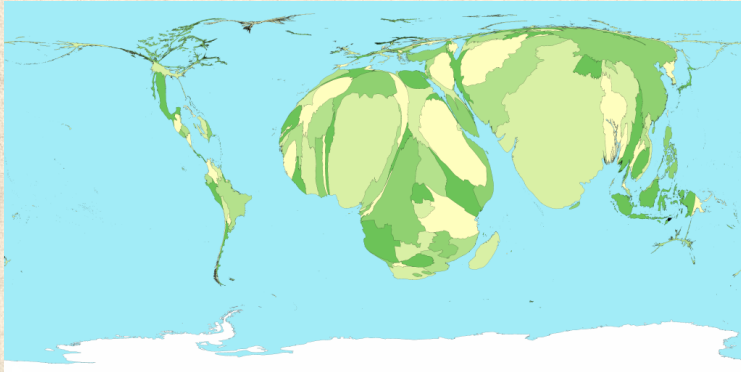
$$\nabla^2 \rho_{\text{pop}} - \frac{\partial \rho_{\text{pop}}}{\partial t} = 0.$$

- ❏ Allow density to diffuse and trace the movement of individual elements and boundaries.
- ❏ Diffusion is constrained by boundary condition of surrounding area having density $\langle \rho \rangle_{\text{pop}}$.



Cartograms

Child mortality:



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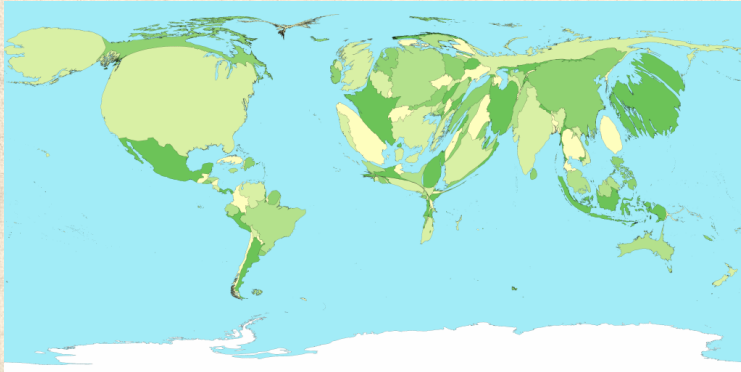
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Energy consumption:



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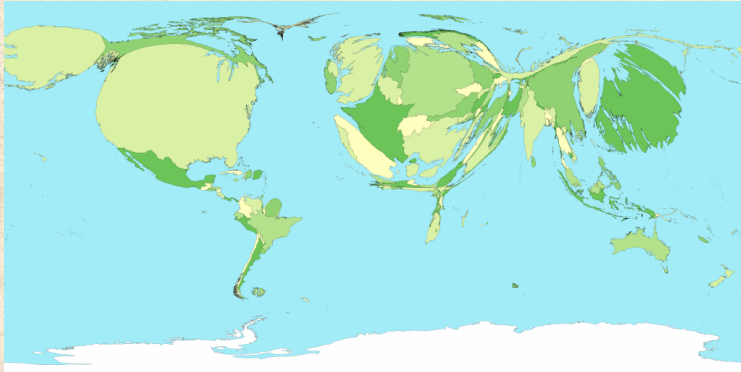
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Gross domestic product:



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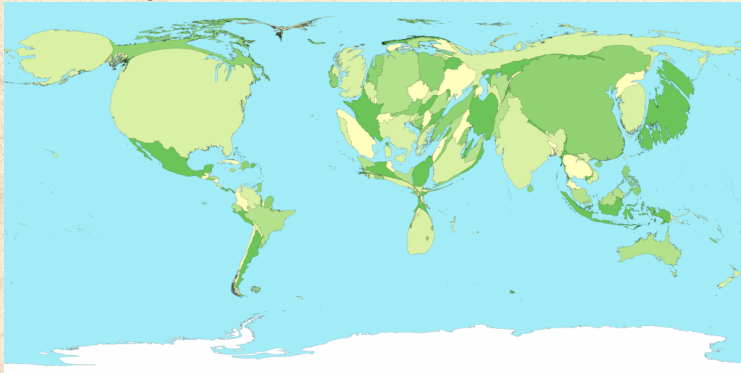
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Greenhouse gas emissions:



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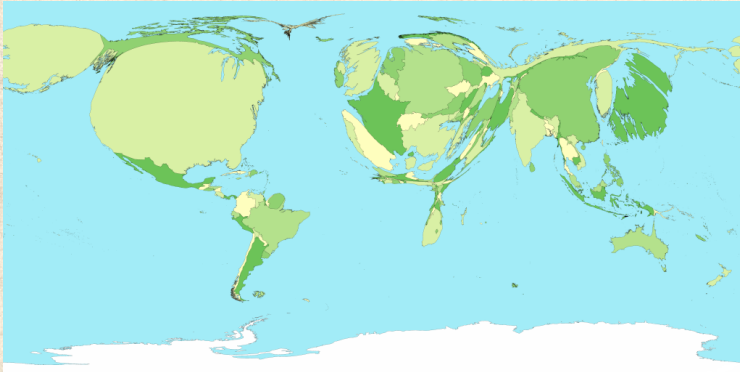
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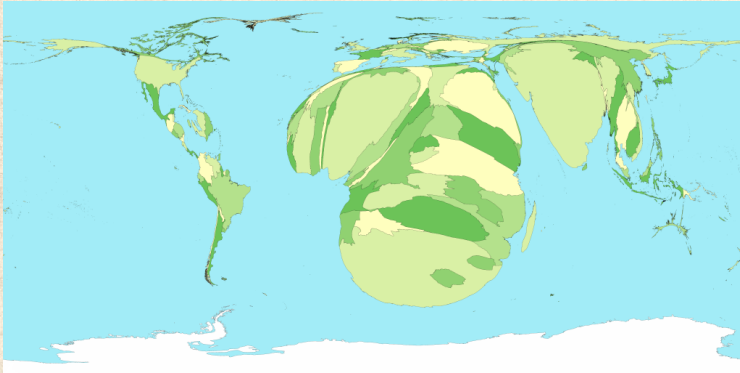
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Spending on healthcare:



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People living with HIV:



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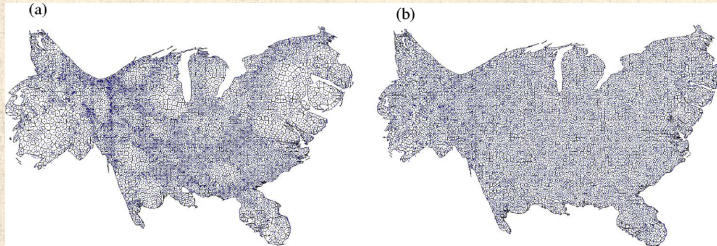
 The preceding sampling of Gastner & Newman's cartograms lives here .

 A larger collection can be found at worldmapper.org .



“Optimal design of spatial distribution networks”

Gastner and Newman,
Phys. Rev. E, **74**, 016117, 2006. ^[2]

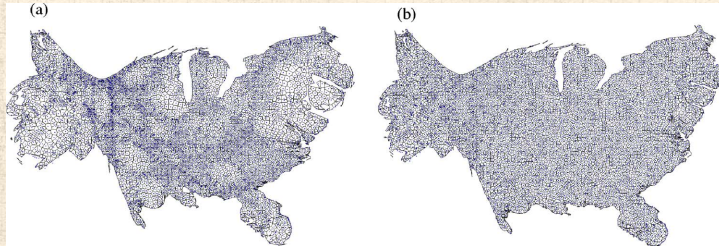


Left: population density-equalized cartogram.



“Optimal design of spatial distribution networks”

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Left: population density-equalized cartogram.



Right: $(\text{population density})^{2/3}$ -equalized cartogram.

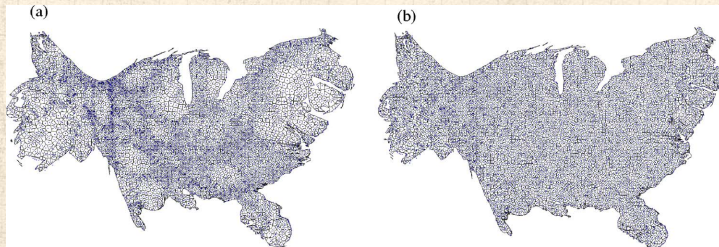




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 **Left:** population density-equalized cartogram.

 **Right:** (population density)^{2/3}-equalized cartogram.

 Facility density is uniform for $\rho_{\text{pop}}^{2/3}$ cartogram.



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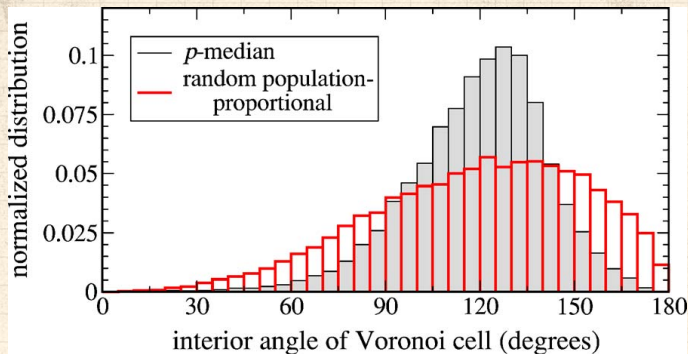
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From Gastner and Newman (2006) ^[2]



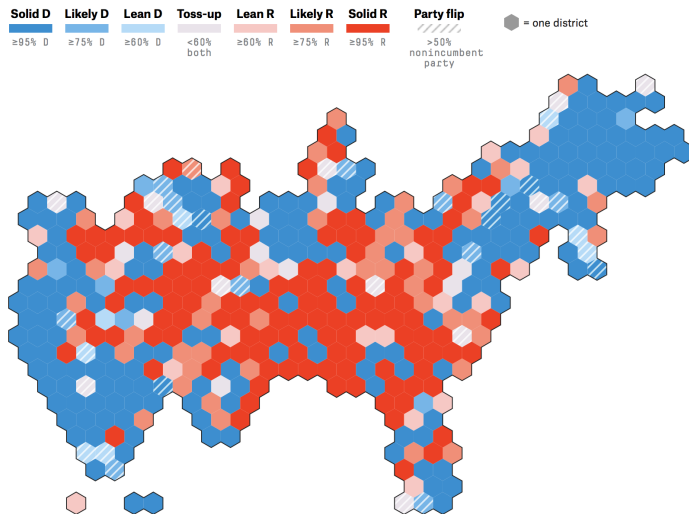
Cartogram's Voronoi cells are somewhat hexagonal.



Better cartograms

Our forecast for every district

The chance of each candidate winning, with all 435 House districts shown at the same size



District totals by category

190

18 8 20

24

48

127

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Let's tessellate: Hexagons for tile grid maps

By [Danny DeBelius](#) | May 11, 2015



A hexagon tile grid, square tile grid and geographic choropleth map. Maps by Danny DeBelius and Alyson Hurt.

As the saying goes, nothing is certain in this life but death, taxes and requests for geographic data to be represented on a map.

For area data, the choropleth map is a tried and true visualization technique, but not without significant dangers depending on the nature of the data and map areas represented. Clarity of mapped state-level data, for instance, is frequently complicated by the reality that most states in the western U.S. carry far more visual weight than the northeastern states.



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Deriving the optimal source distribution:



Basic idea: Minimize the average distance from a random individual to the nearest facility. ^[2]

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Deriving the optimal source distribution:

-  **Basic idea:** Minimize the average distance from a random individual to the nearest facility. ^[2]
-  Assume given a fixed population density ρ_{pop} defined on a spatial region Ω .
-  Formally, we want to find the locations of n sources $\{\vec{x}_1, \dots, \vec{x}_n\}$ that minimizes the **cost function**

$$F(\{\vec{x}_1, \dots, \vec{x}_n\}) = \int_{\Omega} \rho_{\text{pop}}(\vec{x}) \min_i \|\vec{x} - \vec{x}_i\| d\vec{x}.$$

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-  Also known as the p-median problem, and connected to cluster analysis.
-  Not easy ...in fact this one is an NP-hard problem. [2]
-  Approximate solution originally due to Gusein-Zade [3].



Size-density law

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Approximations:



For a given set of source placements $\{\vec{x}_1, \dots, \vec{x}_n\}$, the region Ω is divided up into Voronoi cells, one per source.



Size-density law

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Size-density law

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 As per Stephan's calculation, estimate typical distance from $\vec{x}$ to the nearest source (say i) as

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Approximate c_i as a constant c .



Cost

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Carrying on:



 The cost function is now

$$F = c \int_{\Omega} \rho_{\text{pop}}(\vec{x}) A(\vec{x})^{1/2} d\vec{x}.$$



Carrying on:



The cost function is now

$$F = c \int_{\Omega} \rho_{\text{pop}}(\vec{x}) A(\vec{x})^{1/2} d\vec{x}.$$



Because $A(\vec{x})^{1/2}$ is a constant A_i in any given Voronoi cell Ω_i , the integral over that cell is:

$$\int_{\Omega_i} \rho_{\text{pop}}(\vec{x}) A(\vec{x})^{1/2} d\vec{x} = A_i \int_{\Omega_i} \rho_{\text{pop}}(\vec{x}) d\vec{x}$$



“Don’t don’t constrain on my paraaaaade”

We need something for a Lagrange multiply to multiply:

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We need something for a Lagrange multiply to multiply:



We also have that the **constraint** that Voronoi cells divide up the overall area of Ω : $\sum_{i=1}^n A(\vec{x}_i) = \sum_{i=1}^n A_i = A_{\Omega}$.



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 Sneakily turn this into an integral constraint:

$$\int_{\Omega} \frac{d\vec{x}}{A(\vec{x})} = n.$$

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🧱 Sneakily turn this into an integral constraint:

$$\int_{\Omega} \frac{d\vec{x}}{A(\vec{x})} = n.$$

🧱 Within each cell, $A(\vec{x})$ is constant.

🧱 So ...integral over each of the n cells equals 1.



Now a Lagrange multiplier story:



By varying $\{\vec{x}_1, \dots, \vec{x}_n\}$, minimize

$$G(A) = c \int_{\Omega} \rho_{\text{pop}}(\vec{x}) A(\vec{x})^{1/2} d\vec{x} - \lambda \left(n - \int_{\Omega} [A(\vec{x})]^{-1} d\vec{x} \right)$$



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 I Can Haz Calculus of Variations 

 Compute $\delta G / \delta A$, the functional derivative  of the functional $G(A)$.



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I Can Haz Calculus of Variations ↗?

Compute $\delta G / \delta A$, the functional derivative ↗ of the functional $G(A)$.

This gives

$$\int_{\Omega} \left[\frac{c}{2} \rho_{\text{pop}}(\vec{x}) A(\vec{x})^{-1/2} - \lambda [A(\vec{x})]^{-2} \right] d\vec{x} = 0.$$



Size-density law

Now a Lagrange multiplier story:

 Rearranging, we have

$$A(\vec{x}) = (2\lambda c^{-1})^{2/3} \rho_{\text{pop}}^{-2/3}.$$

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Size-density law

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 Finally, we indentify $1/A(\vec{x})$ as $\rho_{\text{fac}}(\vec{x})$, an approximation of the local source density.



Size-density law

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🧱 Substituting $\rho_{\text{fac}} = 1/A$, we have

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$$\rho_{\text{fac}}(\vec{x}) = \left(\frac{c}{2\lambda} \rho_{\text{pop}} \right)^{2/3}.$$

🧱 Normalizing (or solving for λ):

$$\rho_{\text{fac}}(\vec{x}) = n \frac{[\rho_{\text{pop}}(\vec{x})]^{2/3}}{\int_{\Omega} [\rho_{\text{pop}}(\vec{x})]^{2/3} d\vec{x}} \propto [\rho_{\text{pop}}(\vec{x})]^{2/3}.$$



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Global redistribution networks

One more thing:



How do we supply these facilities?

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Global redistribution networks

One more thing:



How do we supply these facilities?



How do we best redistribute mail? People?

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Global redistribution networks

One more thing:

- How do we supply these facilities?
- How do we best redistribute mail? People?
- How do we get beer to the pubs?

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Global redistribution networks

One more thing:

- How do we supply these facilities?
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- Gastner and Newman model: cost is a function of basic maintenance and travel time:

$$C_{\text{maint}} + \gamma C_{\text{travel}}.$$



Global redistribution networks

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- Travel time is more complicated: Take 'distance' between nodes to be a composite of shortest path distance ℓ_{ij} and number of legs to journey:

$$(1 - \delta)\ell_{ij} + \delta(\text{\#hops}).$$



Global redistribution networks

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- When $\delta = 1$, only number of hops matters.



Global redistribution networks

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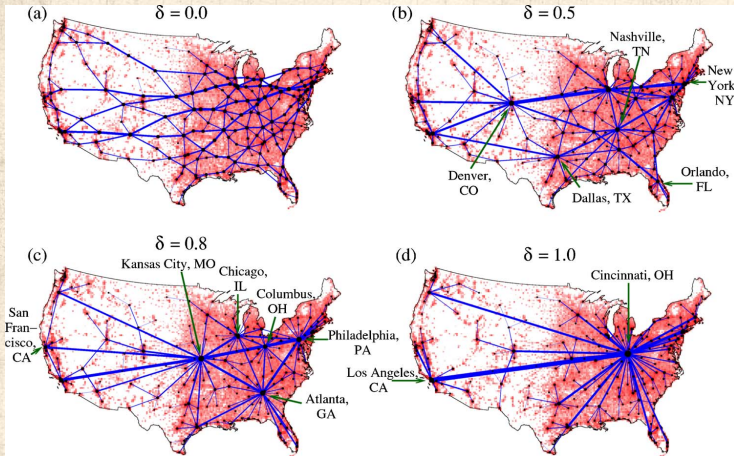
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From Gastner and Newman (2006) ^[2]



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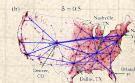
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Public versus private facilities

Beyond minimizing distances:

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Beyond minimizing distances:



“Scaling laws between population and facility densities” by
Um *et al.*, Proc. Natl. Acad. Sci., 2009. [6]

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Beyond minimizing distances:

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Um *et al.* find empirically and argue theoretically that the
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$$\rho_{\text{fac}} \propto \rho_{\text{pop}}^{\alpha}$$

does not universally hold with $\alpha = 2/3$.



Public versus private facilities

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Two idealized limiting classes:

1. For-profit, commercial facilities: $\alpha = 1$;



Public versus private facilities

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Two idealized limiting classes:

1. For-profit, commercial facilities: $\alpha = 1$;
2. Pro-social, public facilities: $\alpha = 2/3$.

Um *et al.* investigate facility locations in the United States and South Korea.



Public versus private facilities: evidence

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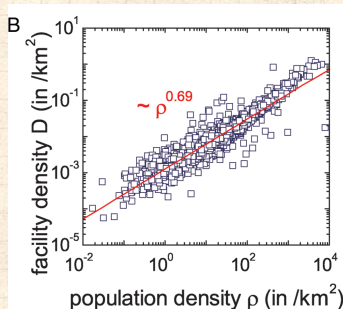
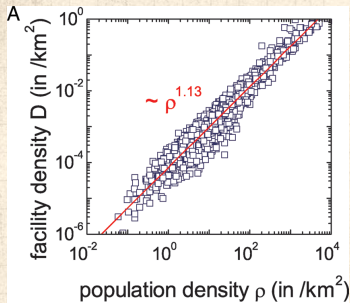
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 **Left plot:** ambulatory hospitals in the U.S.

 **Right plot:** public schools in the U.S.



Public versus private facilities: evidence

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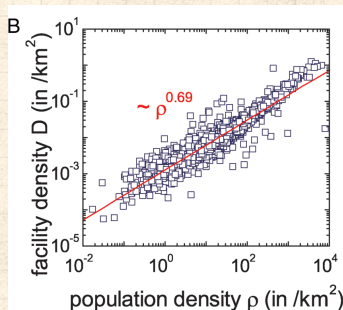
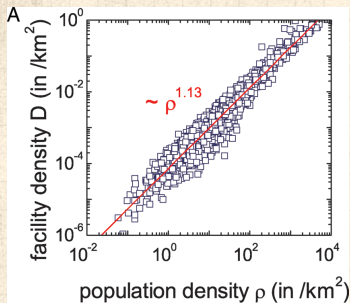
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 **Left plot:** ambulatory hospitals in the U.S.

 **Right plot:** public schools in the U.S.

 **Note:** break in scaling for public schools. Transition from $\alpha \simeq 2/3$ to $\alpha = 1$ around $\rho_{\text{pop}} \simeq 100$.



Public versus private facilities: evidence

US facility	α (SE)	R^2
Ambulatory hospital	1.13(1)	0.93
Beauty care	1.08(1)	0.86
Laundry	1.05(1)	0.90
Automotive repair	0.99(1)	0.92
Private school	0.95(1)	0.82
Restaurant	0.93(1)	0.89
Accommodation	0.89(1)	0.70
Bank	0.88(1)	0.89
Gas station	0.86(1)	0.94
Death care	0.79(1)	0.80
* Fire station	0.78(3)	0.93
* Police station	0.71(6)	0.75
Public school	0.69(1)	0.87

SK facility	α (SE)	R^2
Bank	1.18(2)	0.96
Parking place	1.13(2)	0.91
* Primary clinic	1.09(2)	1.00
* Hospital	0.96(5)	0.97
* University/college	0.93(9)	0.89
Market place	0.87(2)	0.90
* Secondary school	0.77(3)	0.98
* Primary school	0.77(3)	0.97
Social welfare org.	0.75(2)	0.84
* Police station	0.71(5)	0.94
Government office	0.70(1)	0.93
* Fire station	0.60(4)	0.93
* Public health center	0.09(5)	0.19

Rough **transition**
between public and
private at $\alpha \simeq 0.8$.

Note: * indicates
analysis is at
state/province level;
otherwise county
level.



Public versus private facilities: evidence

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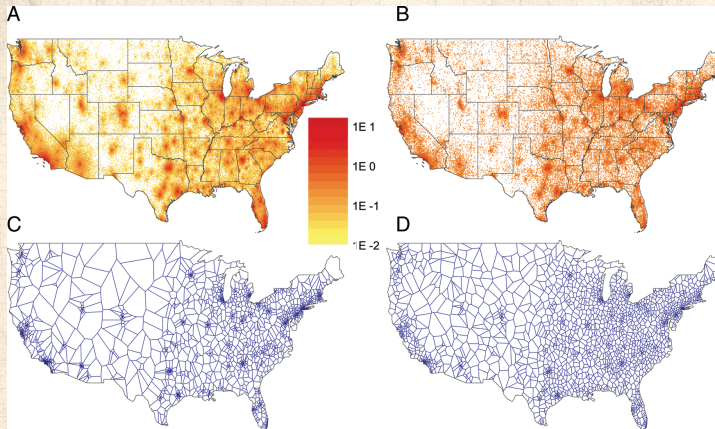
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A, C: ambulatory hospitals in the U.S.; **B, D:** public schools in the U.S.; **A, B:** data; **C, D:** Voronoi diagram from model simulation.



Public versus private facilities: the story

So what's going on?



Social institutions seek to minimize distance of travel.

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Public versus private facilities: the story

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So what's going on?

- ❏ Social institutions seek to **minimize distance of travel**.
- ❏ Commercial institutions seek to **maximize the number of visitors**.
- ❏ Defns: For the i th facility and its Voronoi cell V_i , define
 - ❏ n_i = population of the i th cell;
 - ❏ $\langle r_i \rangle$ = the average travel distance to the i th facility.
 - ❏ A_i = area of i th cell (s_i in Um *et al.* [6])

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Public versus private facilities: the story

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- 🧱 Objective function to maximize for a facility (highly constructed):

$$v_i = n_i \langle r_i \rangle^\beta \text{ with } 0 \leq \beta \leq 1.$$

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Public versus private facilities: the story

So what's going on?

-  Social institutions seek to **minimize distance of travel**.
-  Commercial institutions seek to **maximize the number of visitors**.
-  Defns: For the i th facility and its Voronoi cell V_i , define
 -  n_i = population of the i th cell;
 -  $\langle r_i \rangle$ = the average travel distance to the i th facility.
 -  A_i = area of i th cell (s_i in Um *et al.* [6])
-  Objective function to maximize for a facility (highly constructed):

$$v_i = n_i \langle r_i \rangle^\beta \text{ with } 0 \leq \beta \leq 1.$$

Limits:

-  $\beta = 0$: purely commercial.
-  $\beta = 1$: purely social.



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✉ Either proceeding as per the Gastner-Newman-Gusein-Zade calculation or, as Um *et al.* do, observing that the cost for each cell should be the same, we have:

$$\rho_{\text{fac}}(\vec{x}) = n \frac{[\rho_{\text{pop}}(\vec{x})]^{2/(\beta+2)}}{\int_{\Omega} [\rho_{\text{pop}}(\vec{x})]^{2/(\beta+2)} d\vec{x}} \propto [\rho_{\text{pop}}(\vec{x})]^{2/(\beta+2)}.$$

✉ For $\beta = 0, \alpha = 1$: commercial scaling is linear.



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✉ For $\beta = 0, \alpha = 1$: commercial scaling is linear.

✉ For $\beta = 1, \alpha = 2/3$: social scaling is sublinear.



Return to minimizing average cost in time/resources for
facility allocation:

 Facility locations: $\{\vec{x}_1, \dots, \vec{x}_n\}$.

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Return to minimizing average cost in time/resources for facility allocation:

 Facility locations: $\{\vec{x}_1, \dots, \vec{x}_n\}$.

 Vary locations to minimize cost function:

$$F = c \int_{\Omega} \rho_{\text{pop}}(\vec{x}) A(\vec{x})^{1/2} d\vec{x}.$$



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 Constraint function is on the number of facilities:

$$n = \int_{\Omega} \frac{d\vec{x}}{A(\vec{x})} = \int_{\Omega} [A(\vec{x})]^{-1} d\vec{x}$$

 Issue: Will these facilities all be the same size?²



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²No.

Generalize to m constraints:



We line things up more cleanly:

$$G(A) = c \int_{\Omega} \rho_{\text{pop}}(\vec{x}) A(\vec{x})^{1/2} d\vec{x} + \lambda [A(\vec{x})]^{-1} d\vec{x}.$$

$$G(A) = \int_{\Omega} \rho_{\text{pop}}(\vec{x}) A(\vec{x})^{\alpha} d\vec{x} + \lambda_1 [A(\vec{x})]^{-\beta_1} d\vec{x} + \\ \lambda_2 [A(\vec{x})]^{-\beta_2} d\vec{x} + \dots + \lambda_m [A(\vec{x})]^{-\beta_m} d\vec{x}.$$



Absorb constants into λ s, ignore additive constants.



$[A(\vec{x})]^{-1/d}$: Partition boundary is cost constraint

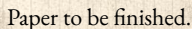


$[A(\vec{x})]^{-1}$: Number of partitions fixed



Only constraint with dominant scaling matters (lowest β)





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