Agent based models: spatial environments

CSCS 530 - Marisa Eisenberg

Space is a critical part of many ABMs!

- Starting from some of the simplest examples like the Schelling model, spatial structure is often a key heterogeneity captured in ABMs
- Important part of many other types of models too
  - Metapopulation models
  - Spatial networks
  - etc!

Types of model environments

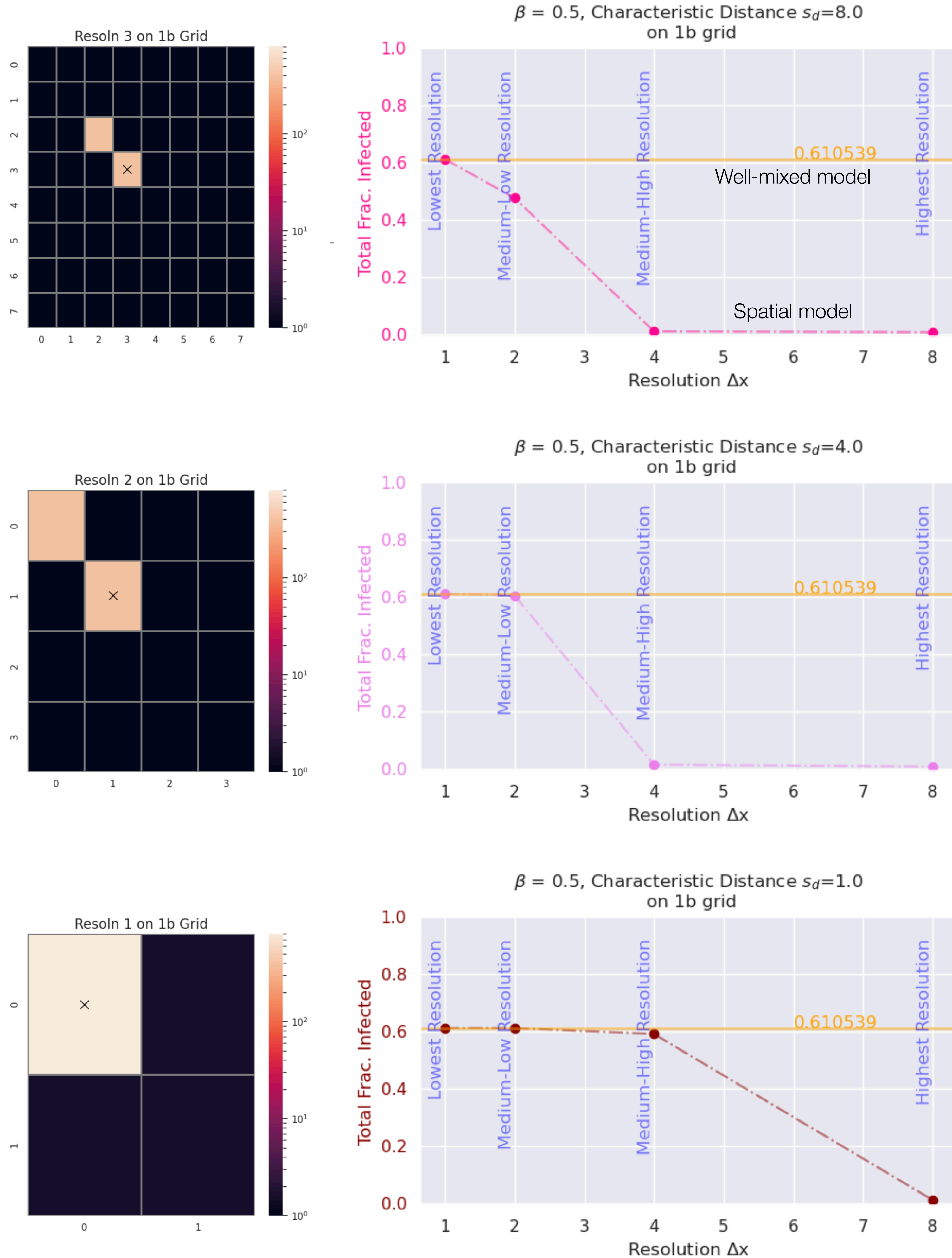
- Non-spatial (or at least, not explicitly spatial)
- Network topologies (may be thought of as spatial or not)
  - E.g. subway networks vs. contact networks
- Explicitly spatial environments
  - Grids
  - 2D or 3D Euclidean or other general space
  - GIS/Mapping/imaging - have agents move through a real-world-based environment

Fun example of emergent properties of the environment

- https://kotaku.com/yes-skyrims-foxes-do-lead-you-to-treasure-sort-of-1847514070

Choice of spatial resolution can strongly affect dynamics!

Depends heavily on assumptions around mixing, population distribution, contact patterns



https://www.medrxiv.org/content/10.1101/2024.10.15.24314208v1.full

Grids

Grids

- We have seen several examples of this (cellular automata, the Shelling model, forest fire model, etc.)
- A classic example along these lines that uses the environment in an active way is **Sugarscape** (slides mostly borrowed from Lynette Shaw)
- Illustrates how explicit interaction with environmental properties (rather than just having the environment act as a passive structure) can alter the dynamics of the system

Sugarscape Model

- Classic, very well-known model of wealth distribution developed in the mid-1990s

- Presented by Joshua Epstein and Robert Axtell in their classic book, *Growing Artificial Societies*

- Begins with a very simple model then explores an extremely wide-range of substantively interesting variations

- Many more variations have been developed since

Classic Sugarscape: Environment

- Agents exist on a square-lattice known as “Sugarscape” w/ individual lattice positions that generate a generic resource called “sugar”
- **Patch variables**
  - Current sugar level, max sugar capacity
- **Patch rules**
  - Patches regenerate sugar according to some function G_{alpha} where alpha = units of sugar grown back in one time step, up to max capacity

Classic Sugarscape: Agents

- **Agent variables**
  - Position: x,y coordinates on the Sugarscape
  - Sugar level: how much sugar agent currently has (no limit)
  - Metabolism (m): how many units of sugar it “burns” per time step
  - Vision (v): how many lattice positions away an agent can “look” for sugar

Classic Sugarscape: Agent actions

- Movement (M):

  1. Look out v number of positions in NWSE directions (no diagonal!)

  2. Move to nearest, unoccupied position w/the most sugar

  3. Collect all sugar on that position

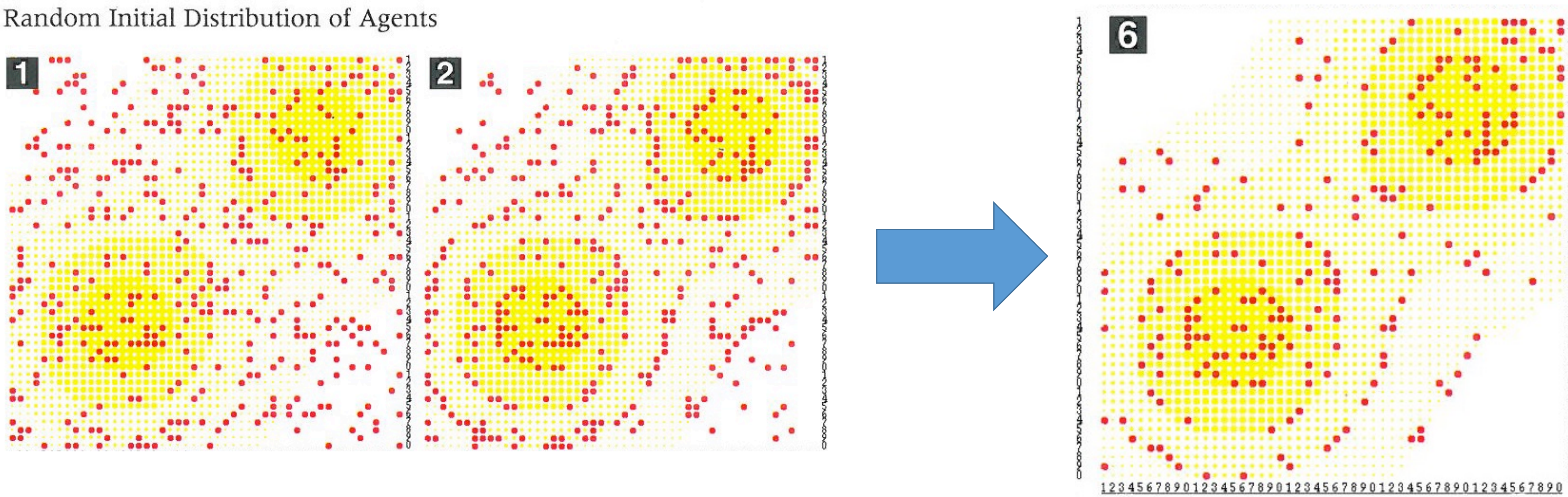
Classic Sugarscape: Agent actions

- Metabolize:
  1. Decrement sugar level by m units
  2. If current sugar level < 0, die

Baseline model for Sugarscape

- Baseline Model:
    - Random initialization of agents for v, m, and initial sugar level
    - Set alpha = infinity (patch regrowth speed)

Animation II-1. Societal Evolution under Rules ({G_∞}, {M}) from a Random Initial Distribution of Agents

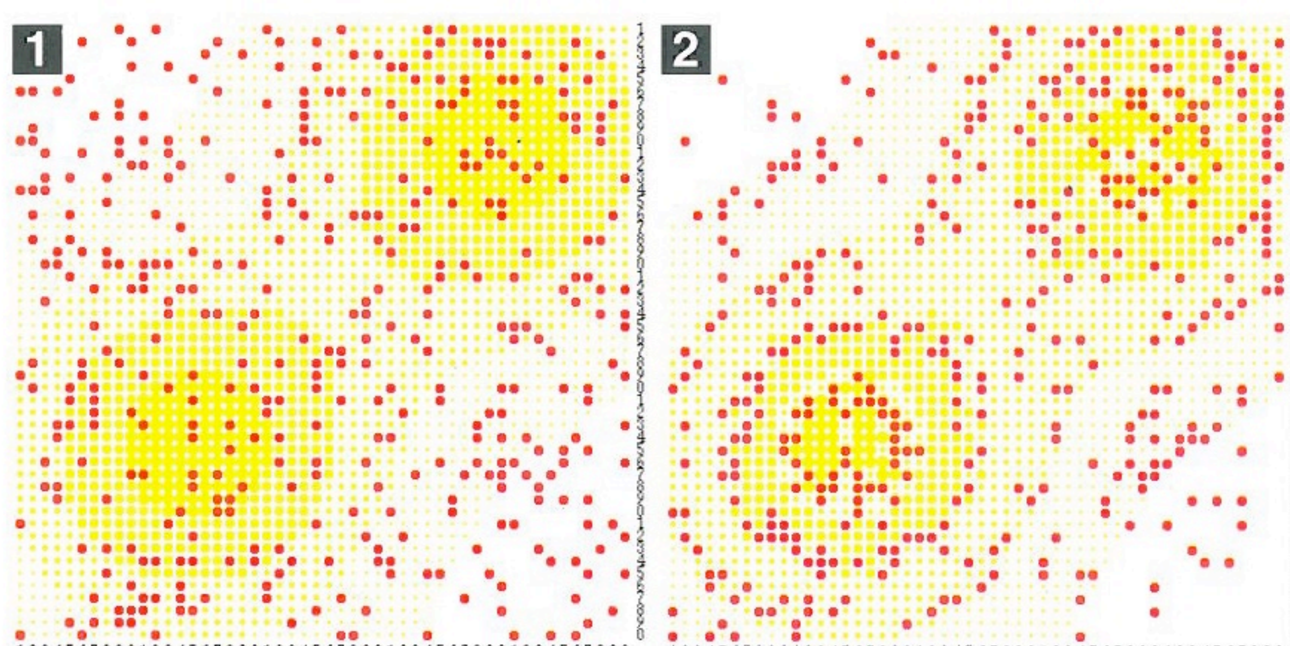


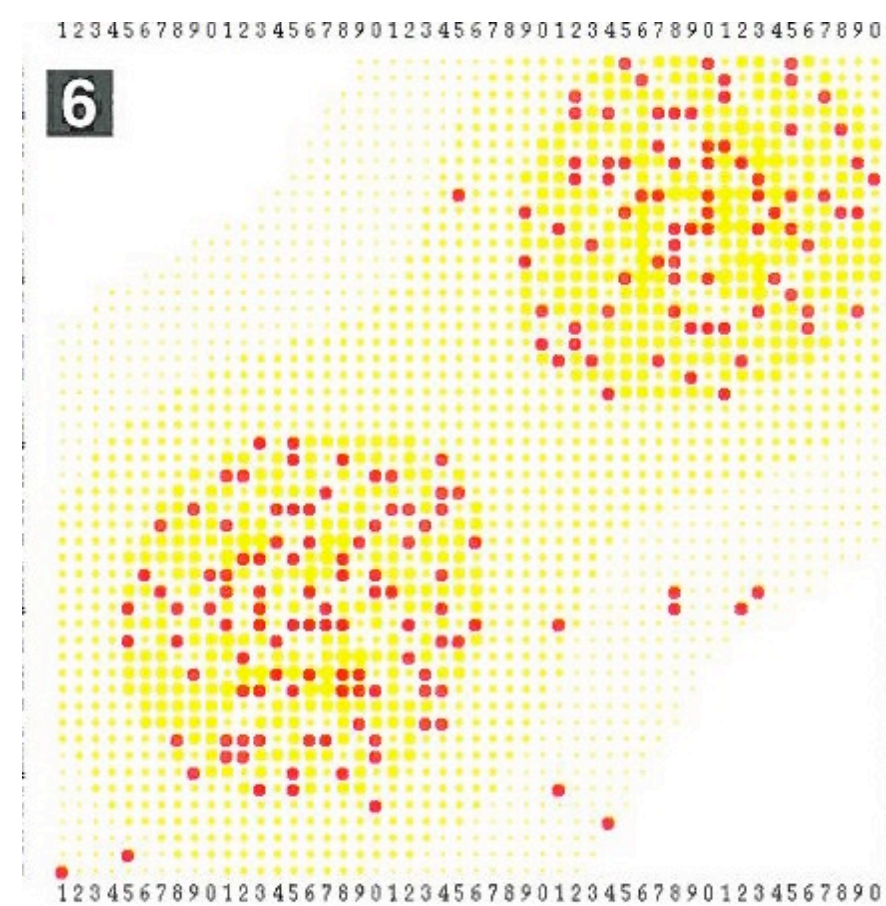
Figures from *Growing Artificial Societies*

Baseline model for Sugarscape

- Baseline Model:
  - Random initialization of agents for v, m, and initial sugar level
  - Set alpha = 1

Animation II-2. Societal Evolution under Rules ({G_1}, {**M**}) from a Random Initial Distribution of Agents





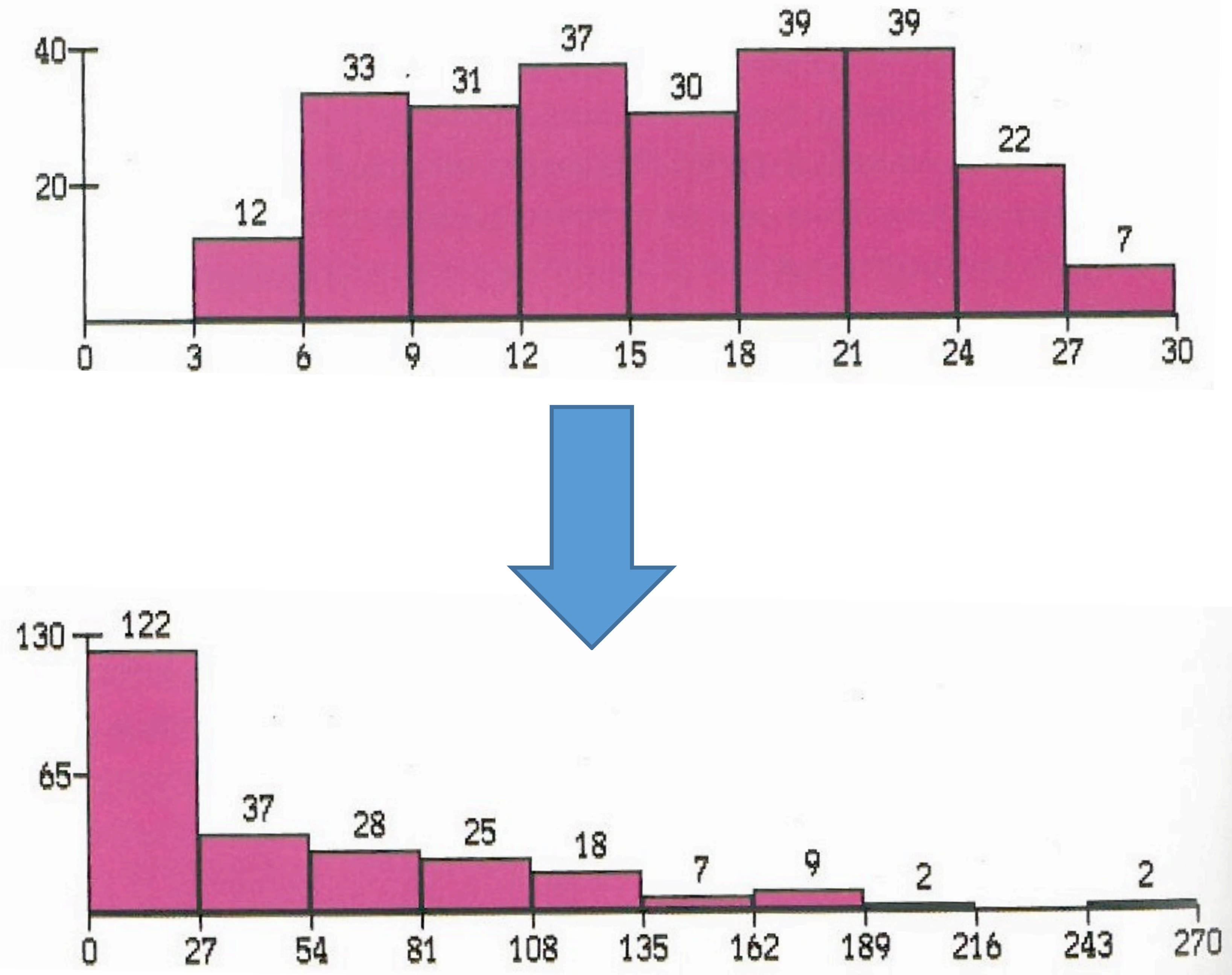
Figures from *Growing Artificial Societies*

Wealth Distributions in Sugarscape

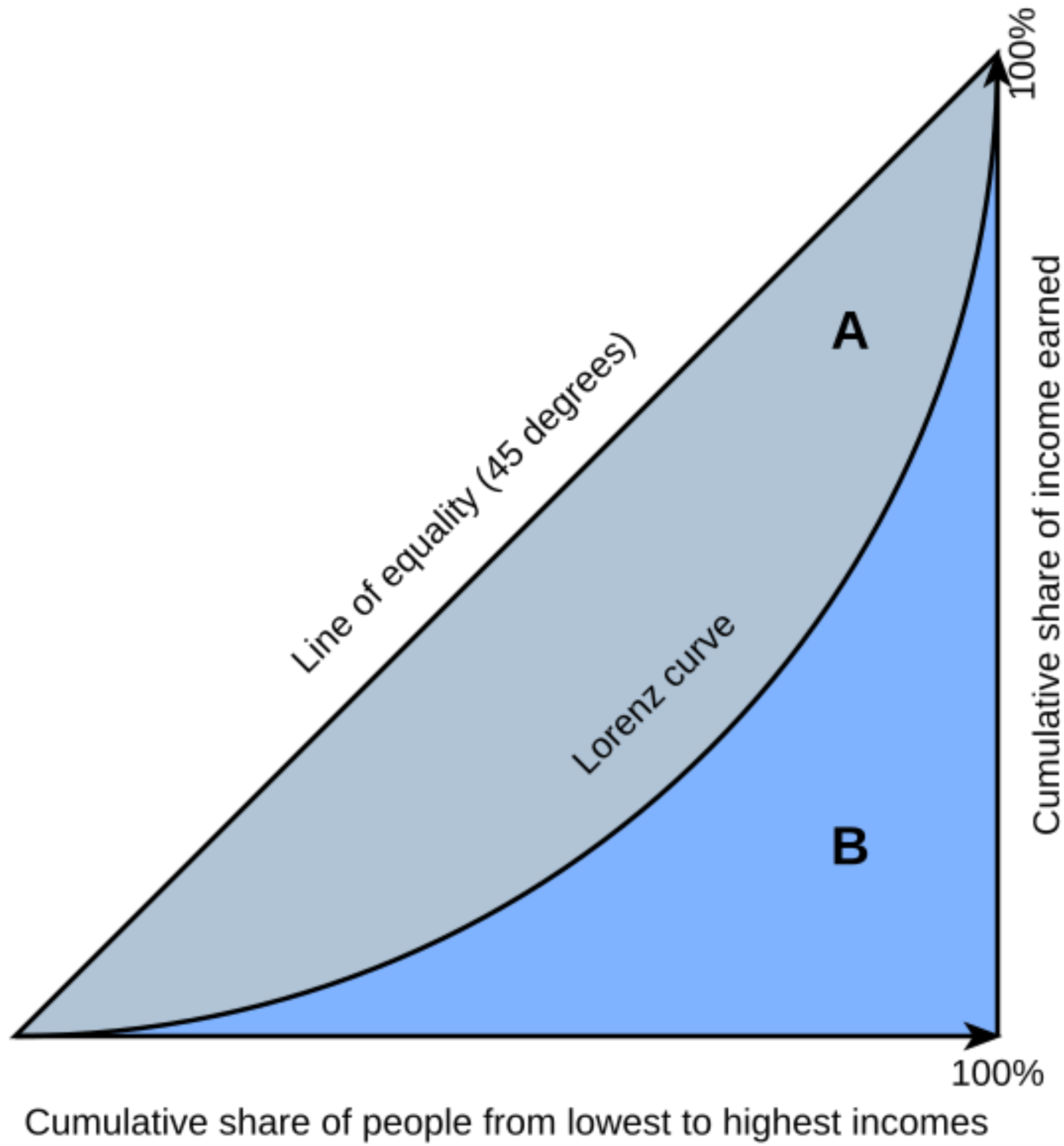
- In baseline model, no replacement for agents that die. Living agents accumulate sugar indefinitely —> no stationary wealth distribution
- Variant: Add Replacement Rule
  - Each agent gets a max achievable age drawn from [a,b]. Die after that age (or before if sugar < 0)
  - When agent dies, replace w/a randomly initialized (including position) agent

Emergence of a skewed wealth distribution

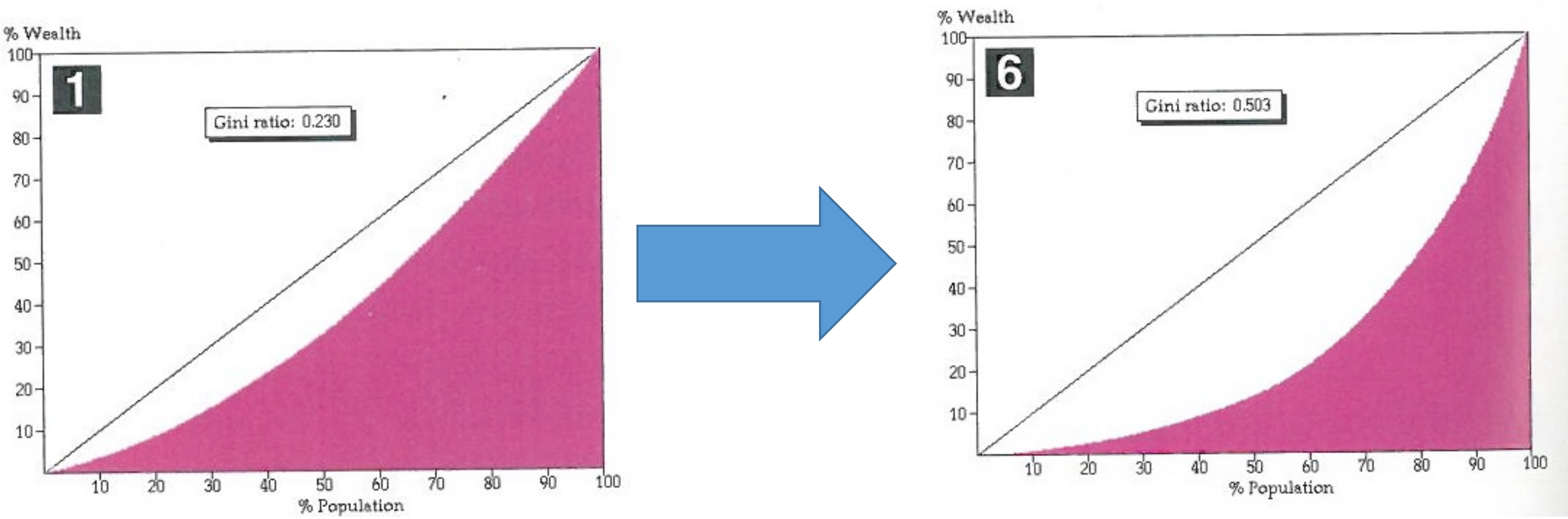
Animation II-3. Wealth Histogram Evolution under Rules ({$\mathbf{G}_1$}, {$\mathbf{M}$, $\mathbf{R}_{[60,100]}$}) from a Random Initial Distribution of Agents



Gini coefficient



Emergence of inequality



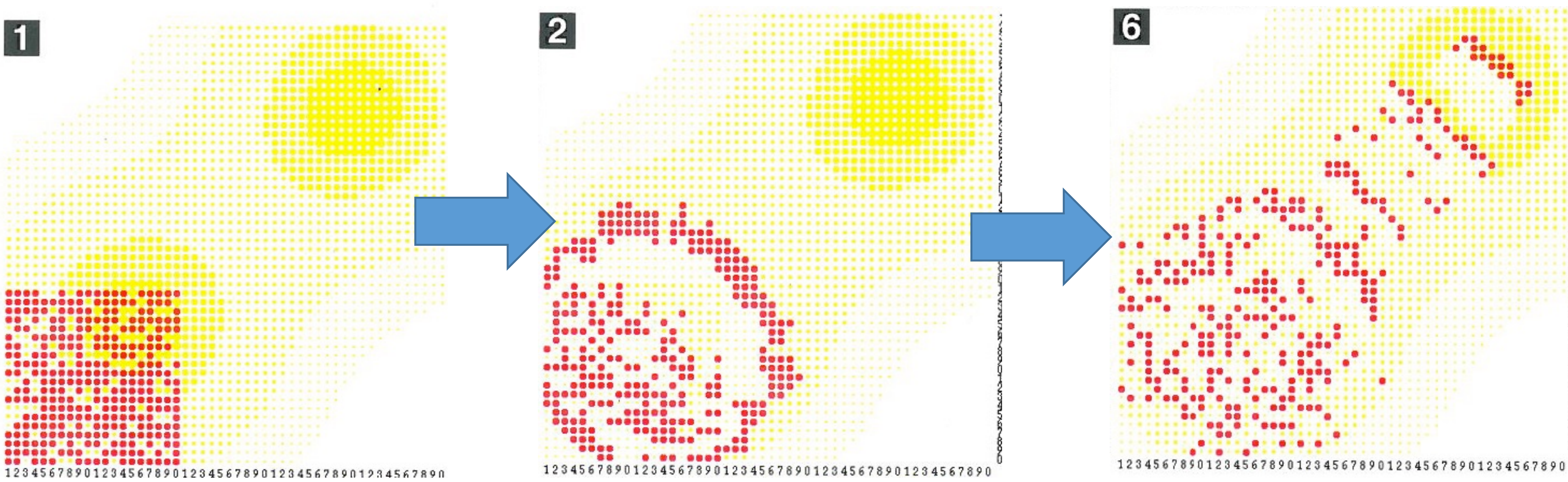
Demonstrates how empirically reminiscent patterns of inequality can emerge from a set of simple rules + environmental and actor heterogeneity

Migration variations

- Alter initial random distribution of agents to add more "structure" in starting position
- Seasonal Migration
  - Introduce spatial and temporal patterning in alpha by creating an "equator" in space and "seasons" of higher-lower alphas in the two regions
  - Note: only environmental changes. No changes to movement/agent rules

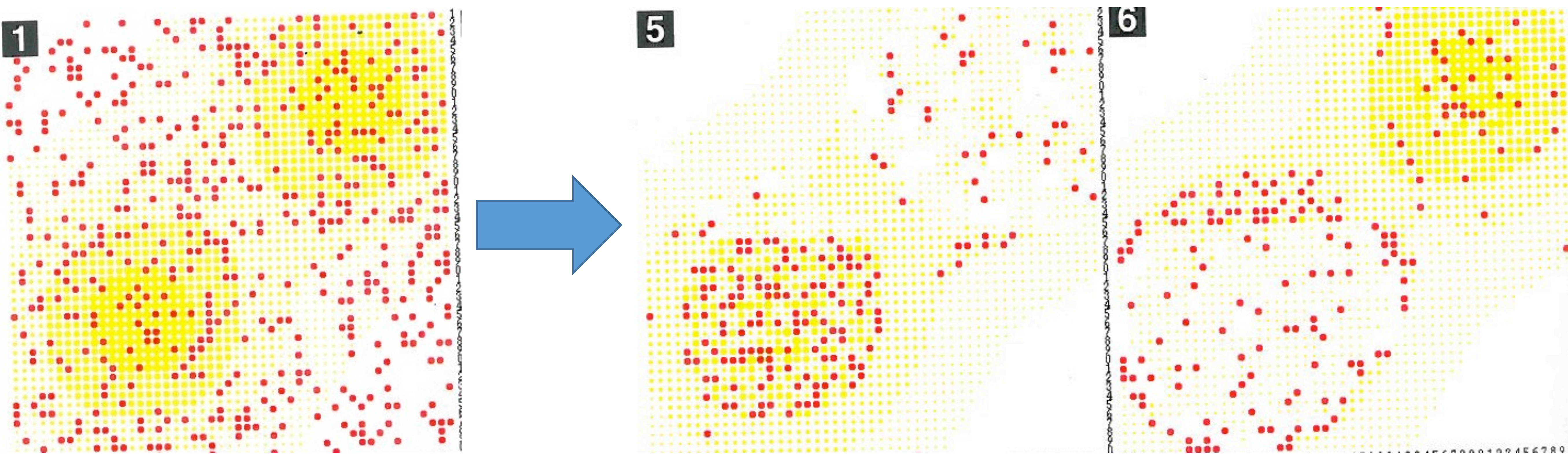
Migration

- Diagonal pattern of movement



Seasonal Migrations

- Migration + emergence of “hibernators” and “migrators”



The World of Sugarscape Elaborations

- Though the baseline model is extremely simple, a wide number of elaborations and variations have been developed to explore a host of other issues
  - Social networks
  - Sexual reproduction
  - Cultural change
  - War and conflict
  - Inheritance and wealth
  - Disease

Sugar and Spice: a Market Dynamics Elaboration

- This elaboration begins with the introduction of a second resource to the environment, “spice”
- Agents now have both a sugar level and a spice level with a corresponding *m* for each. Die if either level < 0
- Movement now changes to be driven by a “Welfare” (W) function

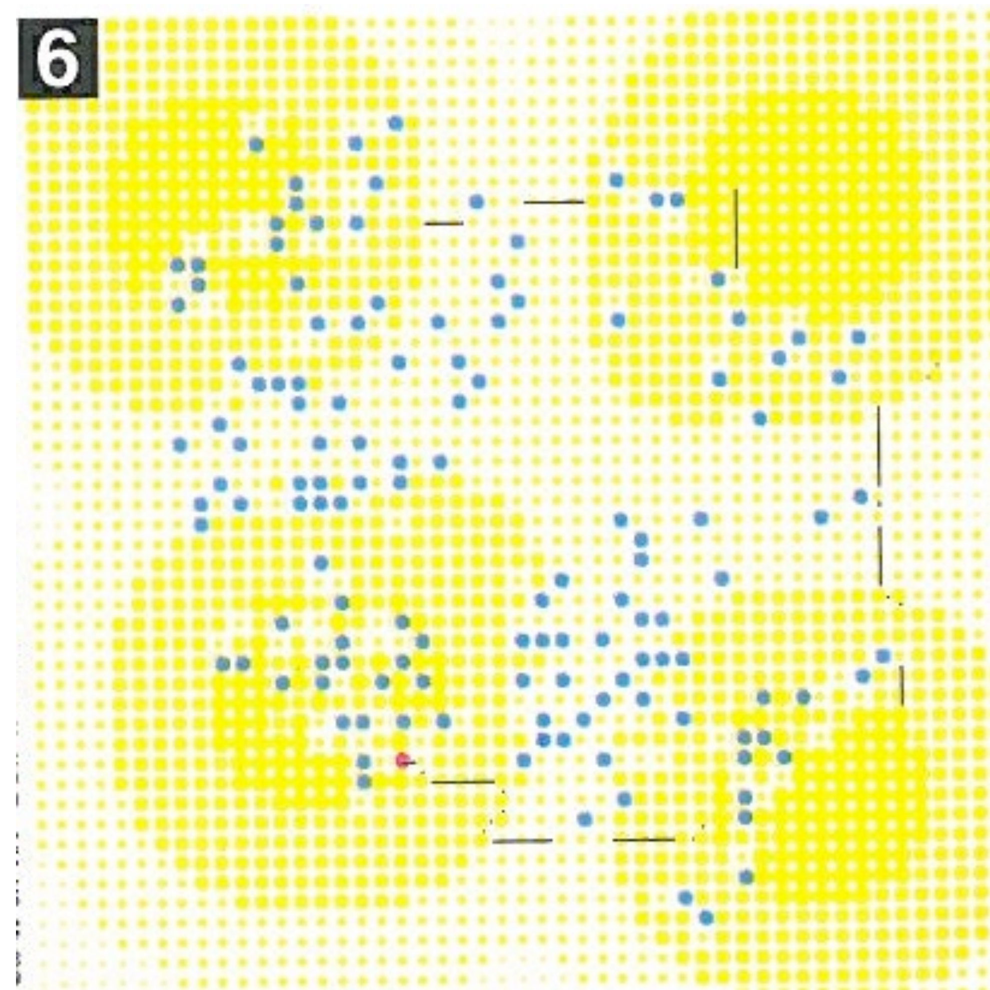
Sugar and Spice: Agent Welfare Function

- 1 = Sugar, 2 = Spice
- $m_T = m_1 + m_2.$

  $W(w_1, w_2) = w_1^{m_1/m_T} w_2^{m_2/m_T},$
- Movement Rule Change:
- Replace “unoccupied position with maximum sugar level” with “unoccupied position maximum welfare increase”

Sugar and Spice: No Trade

- Oscillating movements between Sugar and Spice piles
- Lower carrying capacity than 1 commodity scenario



Sugar and Spice: Trade Rules

- With 2 commodities, can now allow for decentralized trade between agents
- Marginal Rate of Substitution (MRS) $\dfrac{\frac{w_2}{m_2}}{\frac{w_1}{m_1}}$

	$MRS_A > MRS_B$		$MRS_A < MRS_B$	
Action	A	B	A	B
Buys	sugar	spice	spice	sugar
Sells	spice	sugar	sugar	spice

Sugarscape

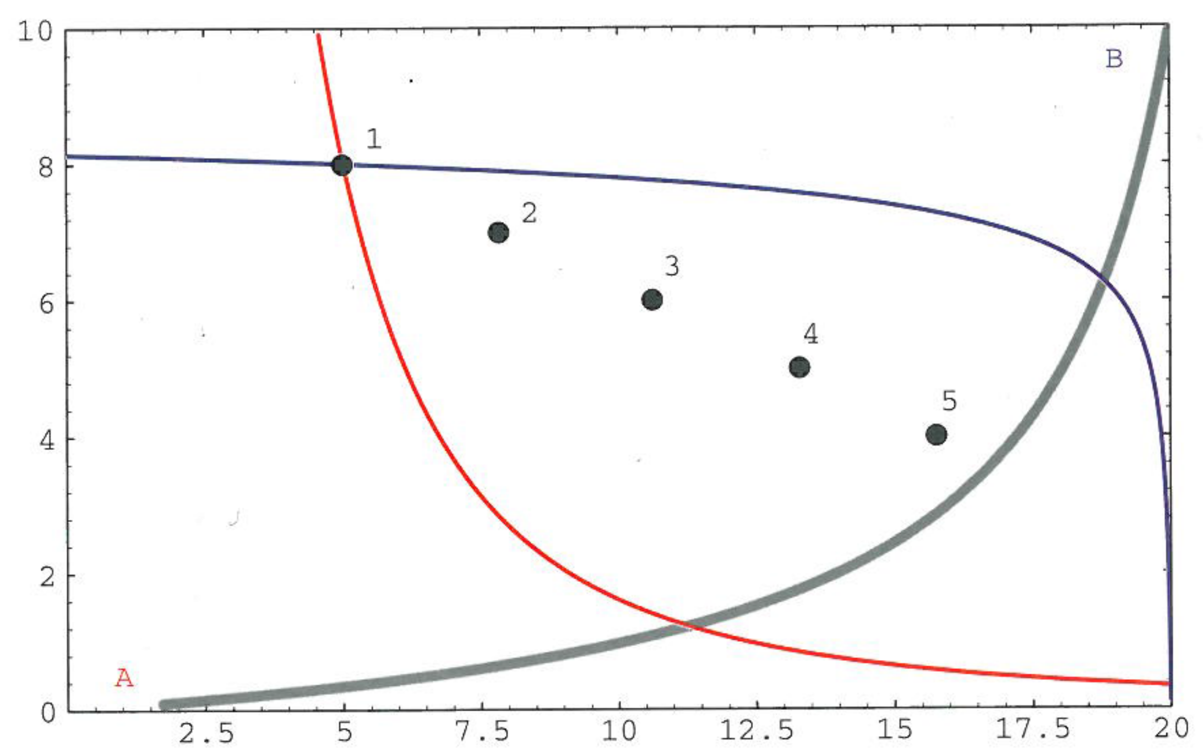
Agent trade rule **T**:

- Agent and neighbor compute their *MRS*s; if these are equal then end, else continue;
- The direction of exchange is as follows: spice flows from the agent with the higher *MRS* to the agent with the lower *MRS* while sugar goes in the opposite direction;
- The geometric mean of the two *MRS*s is calculated—this will serve as the price, p;
- The quantities to be exchanged are as follows: if $p > 1$ then p units of spice for 1 unit of sugar; if $p < 1$ then $1/p$ units of sugar for 1 unit of spice;
- If this trade will (a) make both agents better off (increases the welfare of both agents), and (b) not cause the agents' *MRS*s to cross over one another, then the trade is made and return to start, else end.

Sugarscape

- Local Pareto Optimality
- Can show that these rules for exchange and price formation, played out multiple times in a bargaining dyad, achieves a local Pareto optimum

Figure IV-2. Edgeworth Box Representation of Two Agents Trading according to Rule **T**



Sugarscape

- Decentralized trading can lead to a stable, average trade price w/o the need for a central "auctioneer"

- Also, increases carrying capacity of system

Figure IV-3. Typical Time Series for Average Trade Price under Rule System ({$\mathbf{G}_1$}, {**M**, **T**})

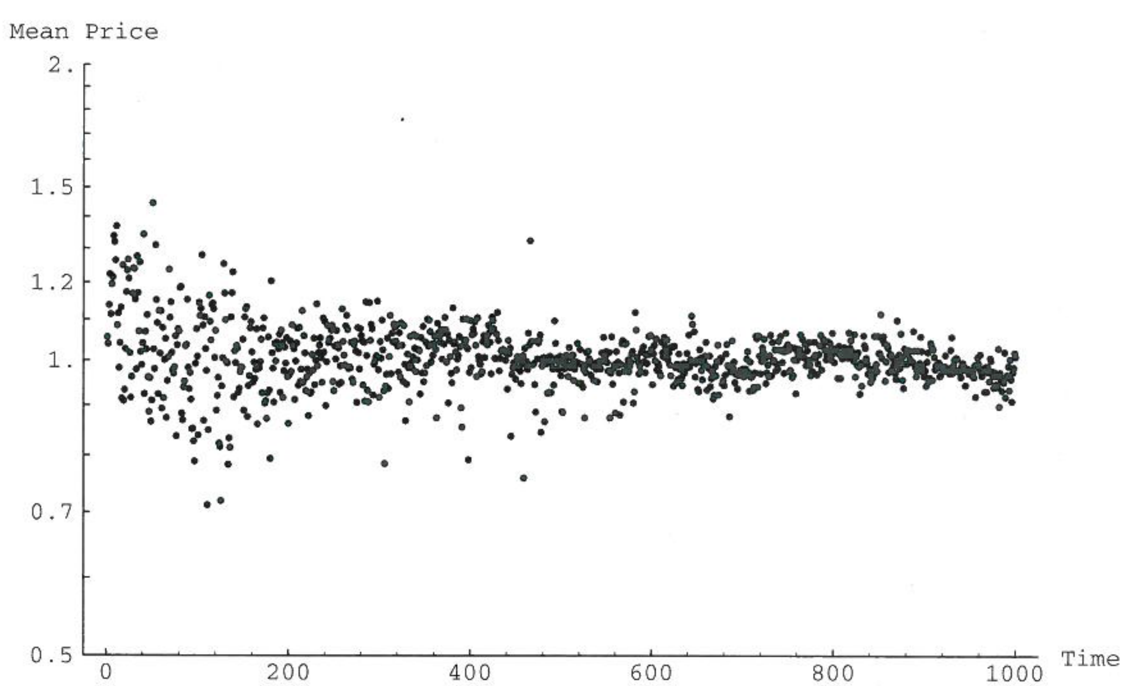
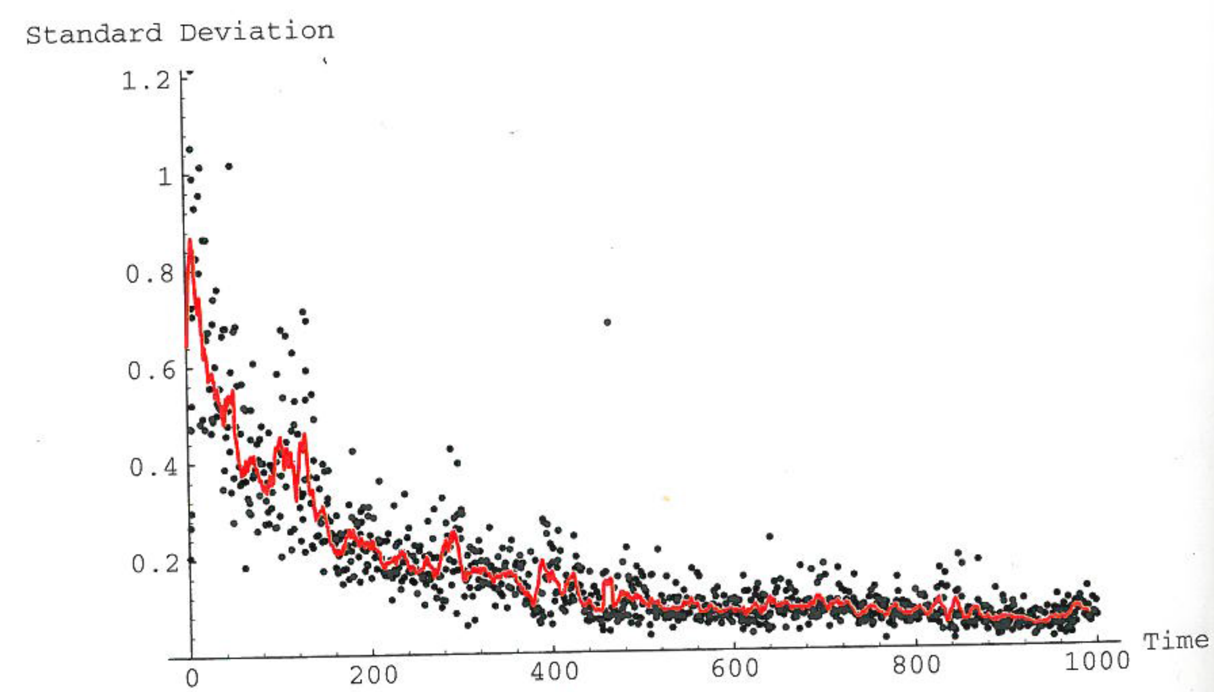


Figure IV-5. Typical Time Series for the Standard Deviation in the Logarithm of Average Trade Price under Rule System ({$\mathbf{G}_1$}, {**M**, **T**})



Sugarscape extensions

- Horizontal inequality
- Ability to get into “Far From Equilibrium Economics”
- Price variance strongly impacted by agent vision
- Local efficiency, Global inefficiency

Abstract 2D and 3D space

2D or 3D space

- 2D space
  - Abstract 2D spaces with arbitrary setups but not on an explicit grid (e.g. movement is decided based on a distribution not on a grid)
  - Imaging data (e.g. MRI, microscopy imaging)
  - Map data
- 3D space
  - Often used for flocking simulations (e.g. Boids)
  - Also for modeling complex biological or physical domains (e.g. cellular environments, etc.)

Abstract 2D & 3D space

- We have worked with several examples of this in 2D space (e.g. rabbits/foxes)

- Complex environments can be generated

Swarming model: Boids

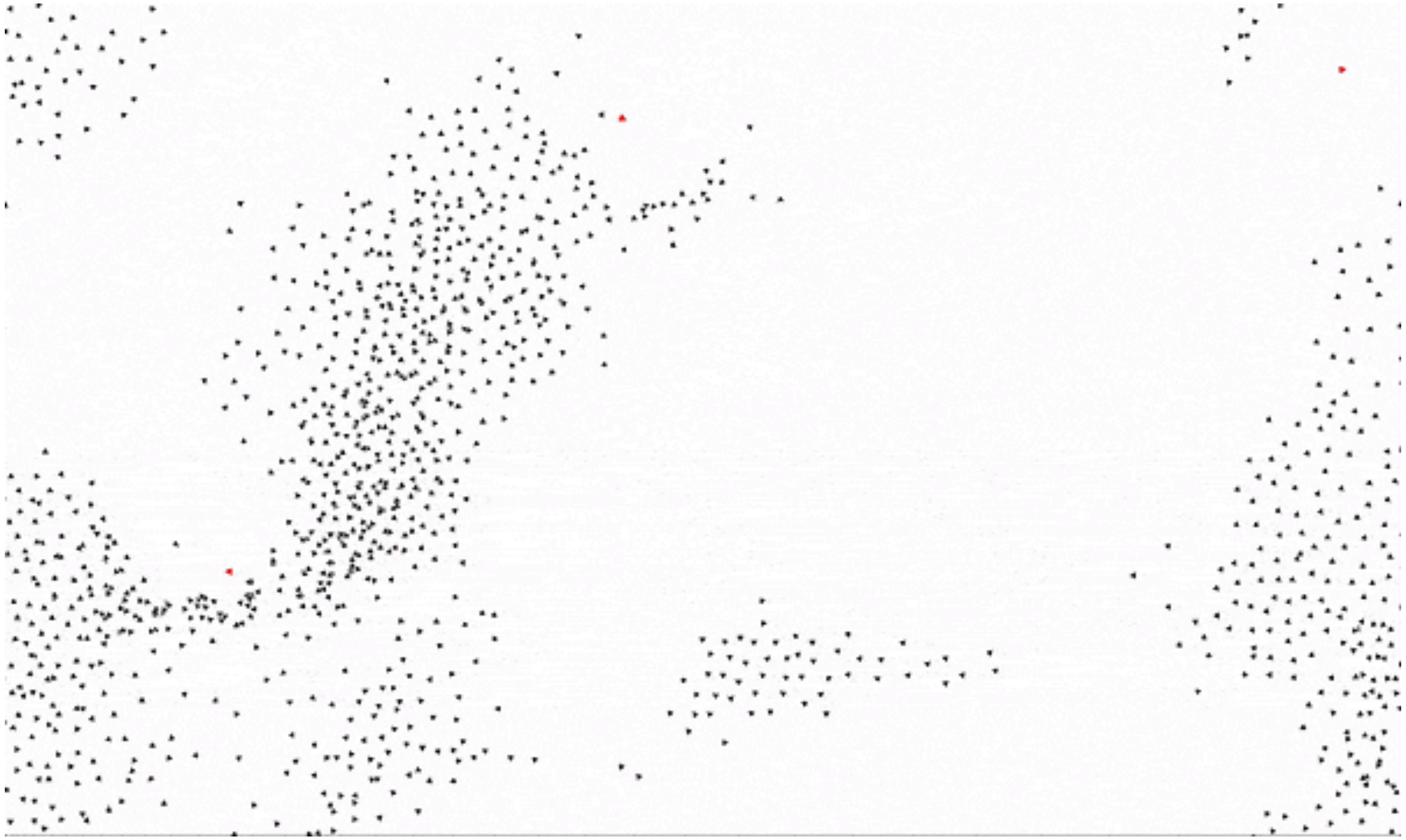
- Classic example of emergence
- Can be run in 2D or 3D space
- 3 basic rules
  - **Separation**: steer to avoid crowding local flockmates
  - **Alignment**: align direction with average heading of local flockmates
  - **Cohesion**: steer to move towards the average position (center of mass) of local flockmates

Boids

- Basic version: https://eater.net/boids
- There are many variations!
    - Add predators
    - Obstacles to navigate
    - Winds/currents
    - Goals/searching (food, nests/shelter, etc.)

Obstacle avoidance examples

- https://www.youtube.com/watch?v=6dJlhv3hfQ0
- https://www.youtube.com/watch?v=bqtqltqcQhw
- (need to skip ahead to the relevant parts)
- Predator example



Boids

- Often used in video games, movies, etc.

- Also used in swarm robotics

Agent simulations of learning to navigate an environment

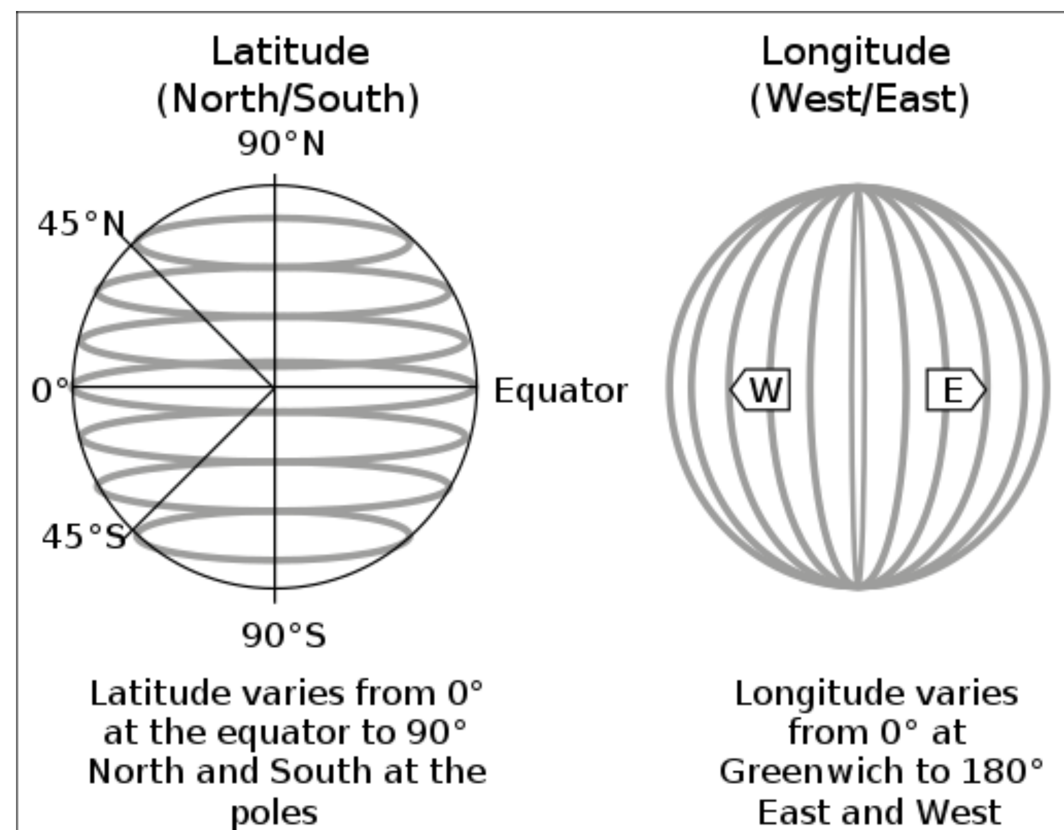
- Google deepmind: https://www.youtube.com/watch?v=gn4nRCC9TwQ

Maps, GIS, imaging, and real world environments

Mapping data

- An ABM using mapping/GIS data is basically an ABM on a grid or 2D space!
  - (With some kind of projection, but this often doesn't matter much)

- It's just that the structure and visualization of the data is based on the real world



Mapping data

- Often used for modeling commuting patterns, disease spread, social dynamics, etc.

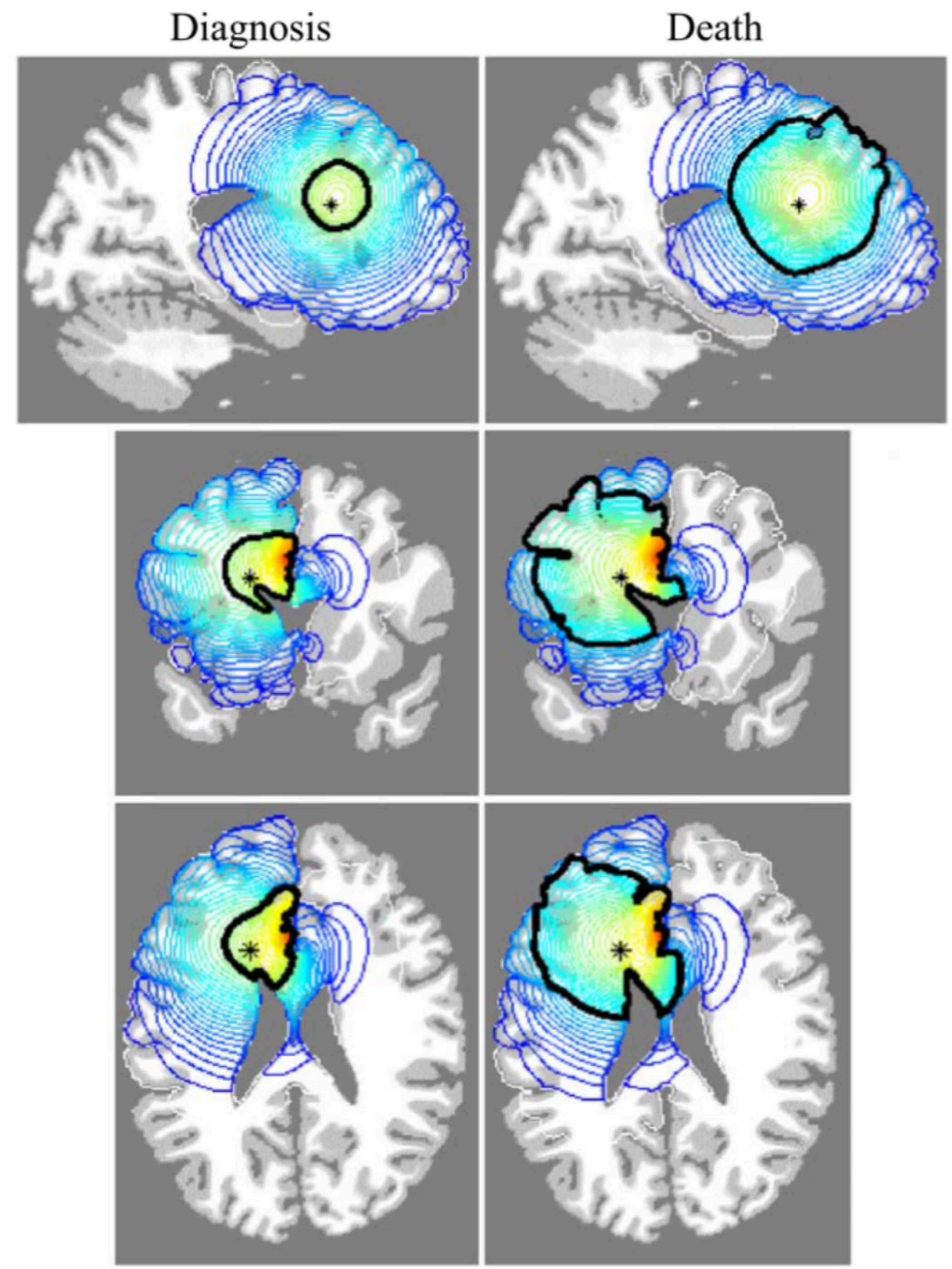
- Modeling with mapping is similar to other ABM with space, just using the map to determine where features are

- Example: FRED synthetic population model

- https://fred.publichealth.pitt.edu/measles

Imaging data

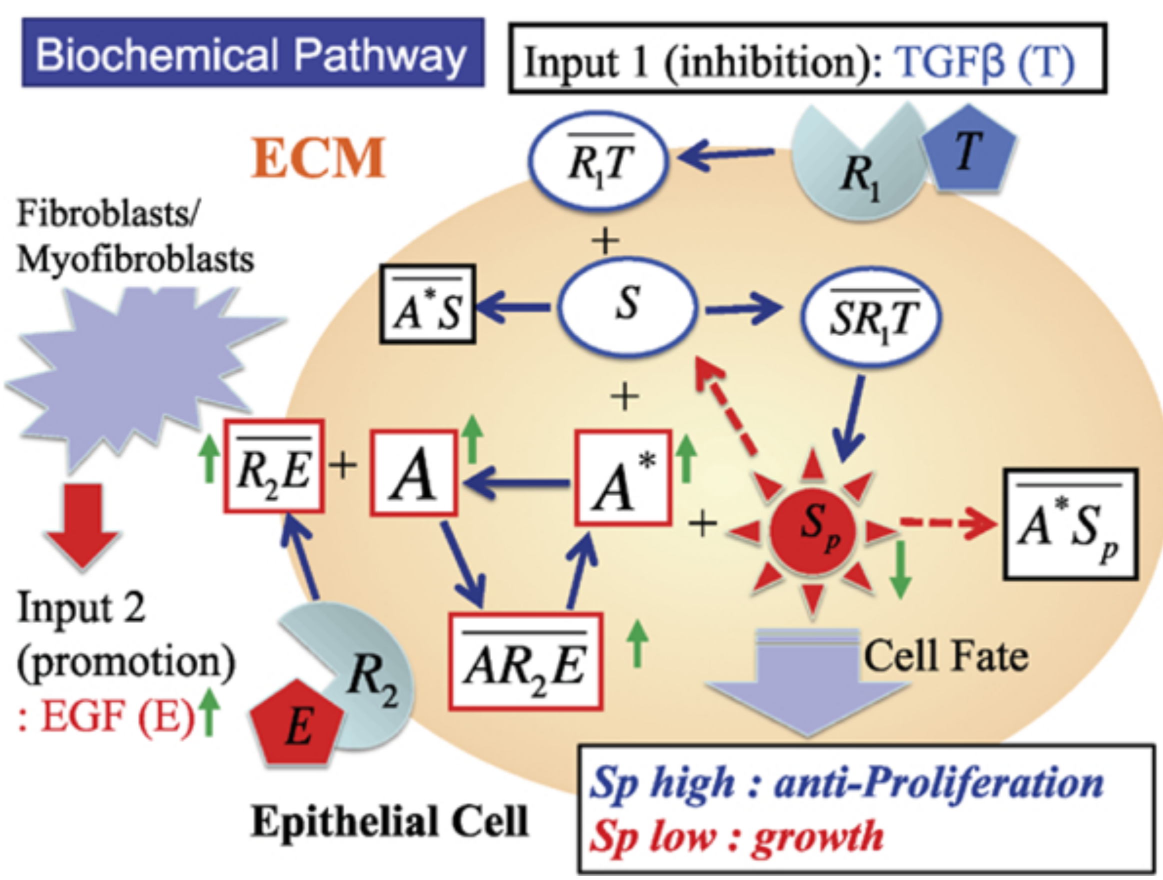
- Exists at many scales — landscapes to cells
- Often requires some image processing to identify regions with key features for the agents to interact with
- We've seen another example of this in the model of the Ancestral Puebloan communities that we looked at previously

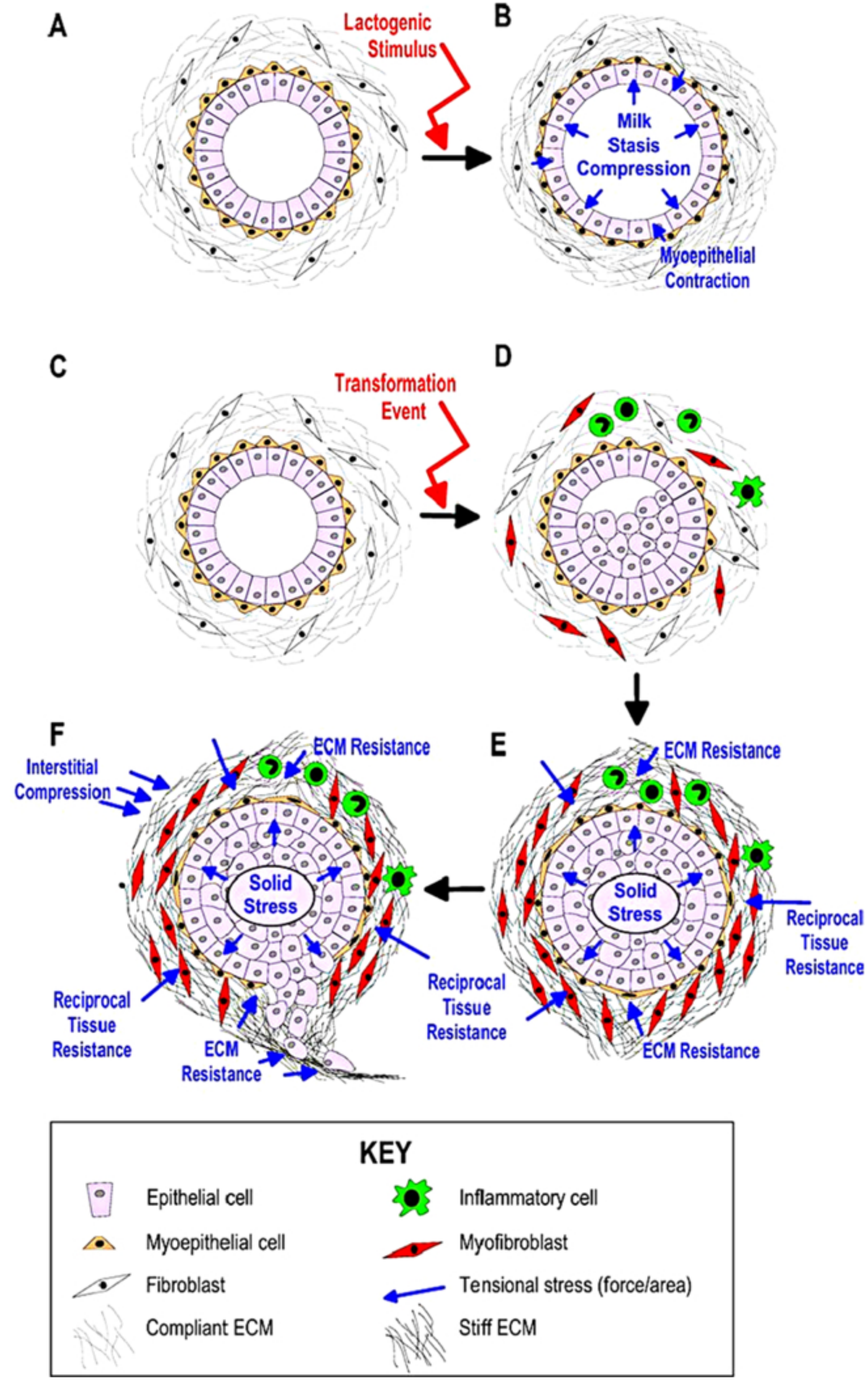


Swanson et al. 2003 Virtual and real brain tumors: using mathematical modeling to quantify glioma growth and invasion

Example: hybrid model of breast cancer dynamics

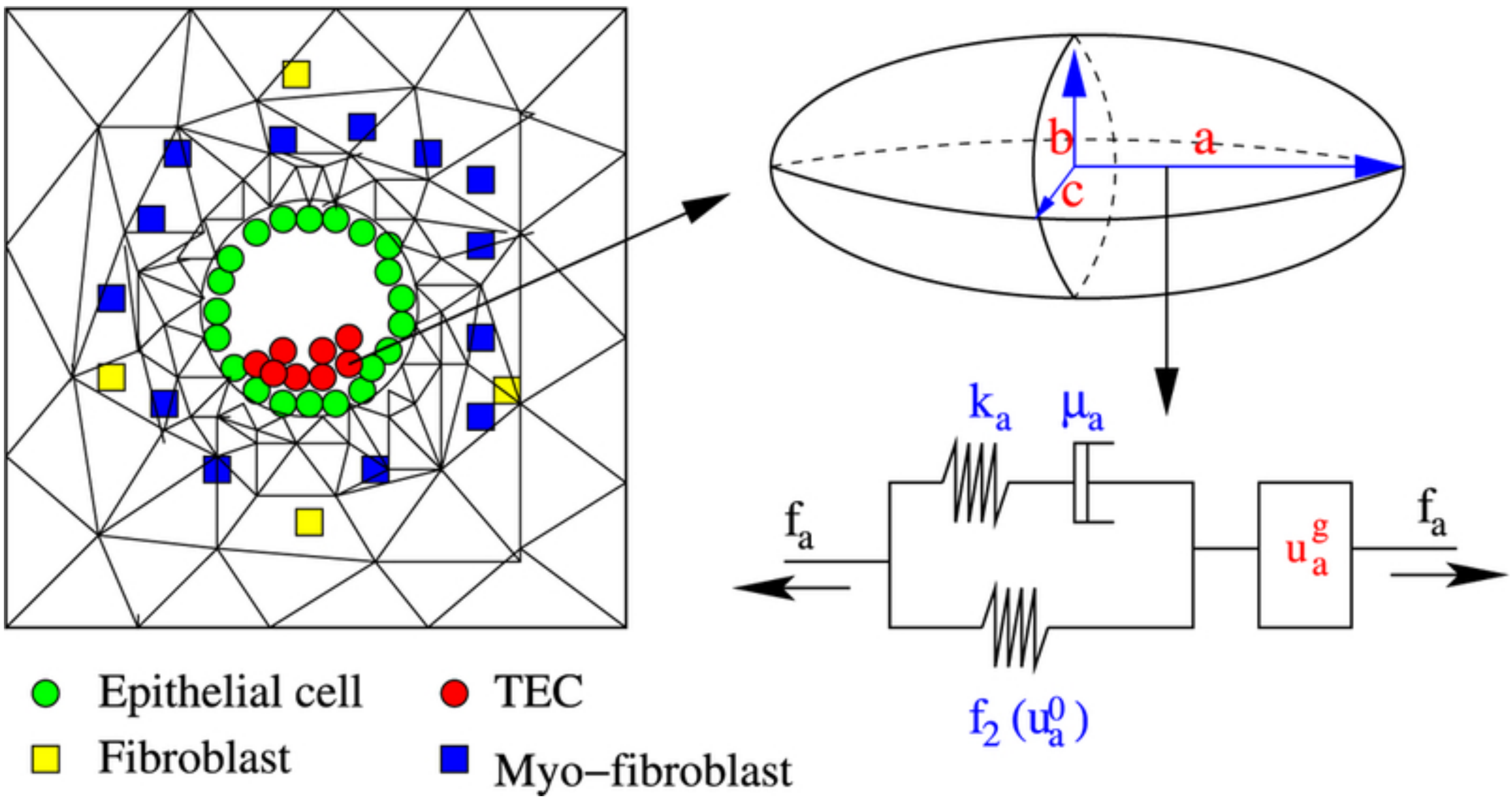
- Transformation from normal ducts to solid tumor in breast cancer



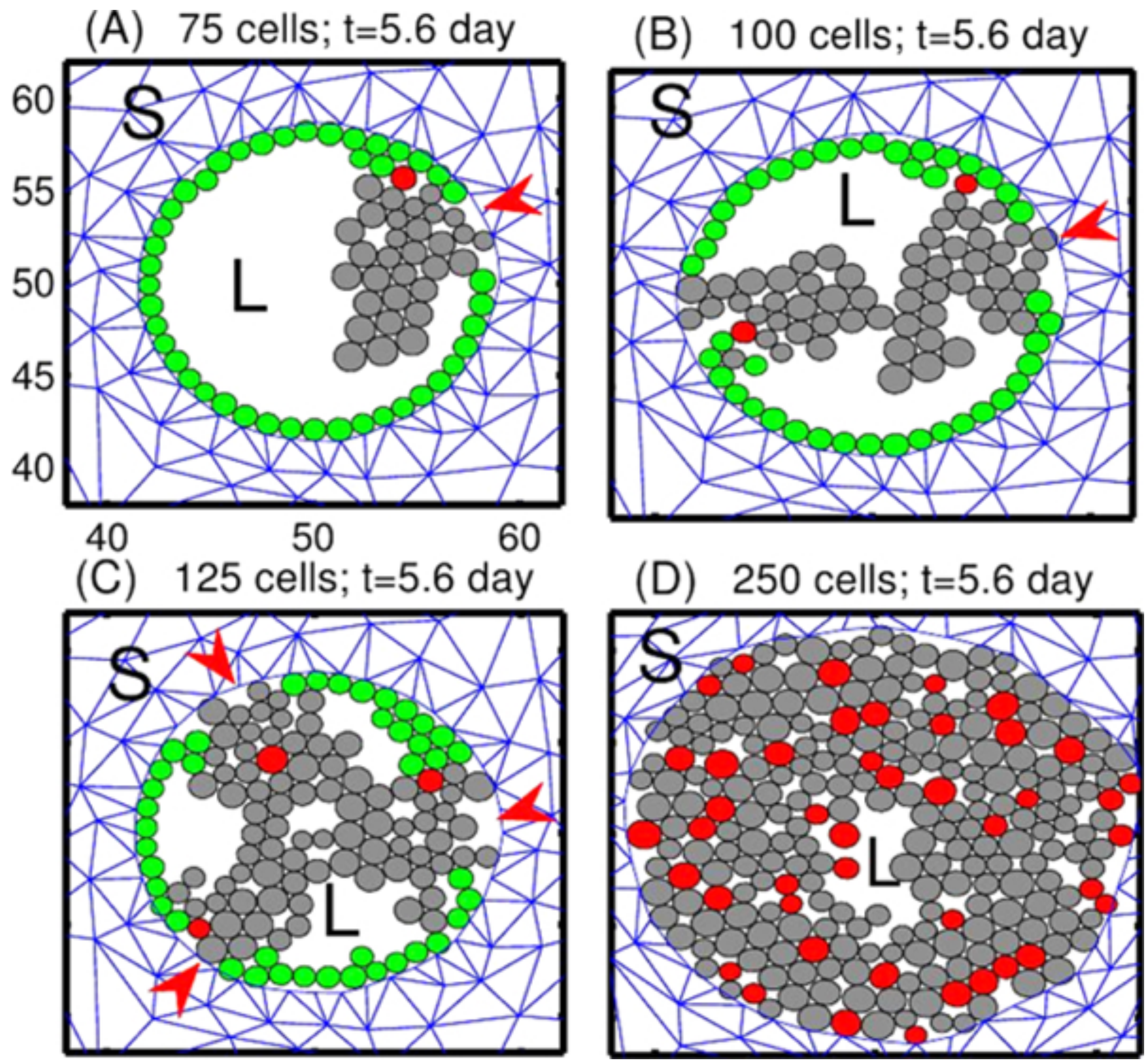


Kim & Friedman - https://www.ncbi.nlm.nih.gov/pubmed/23292359

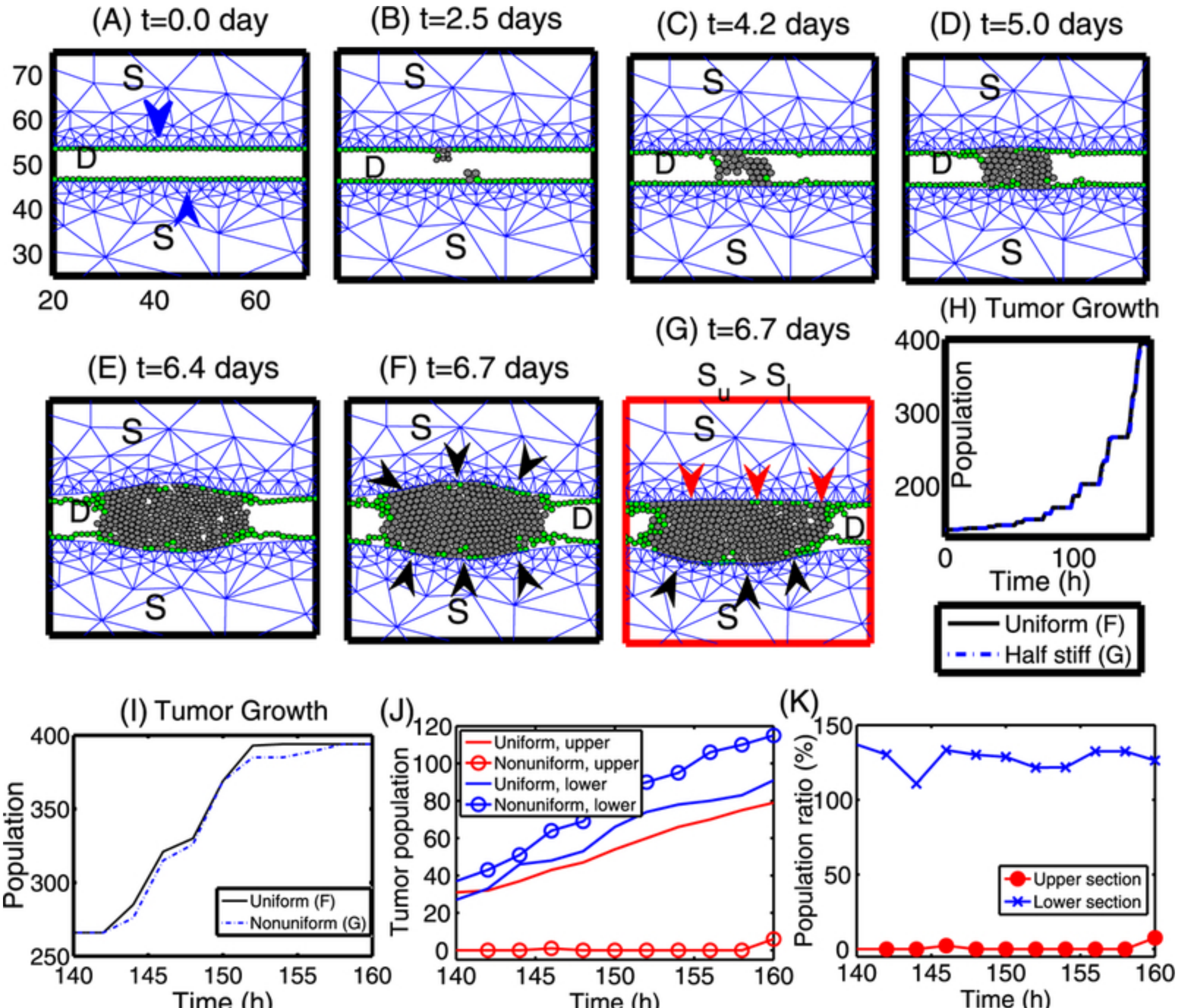
Cells as agents within the duct

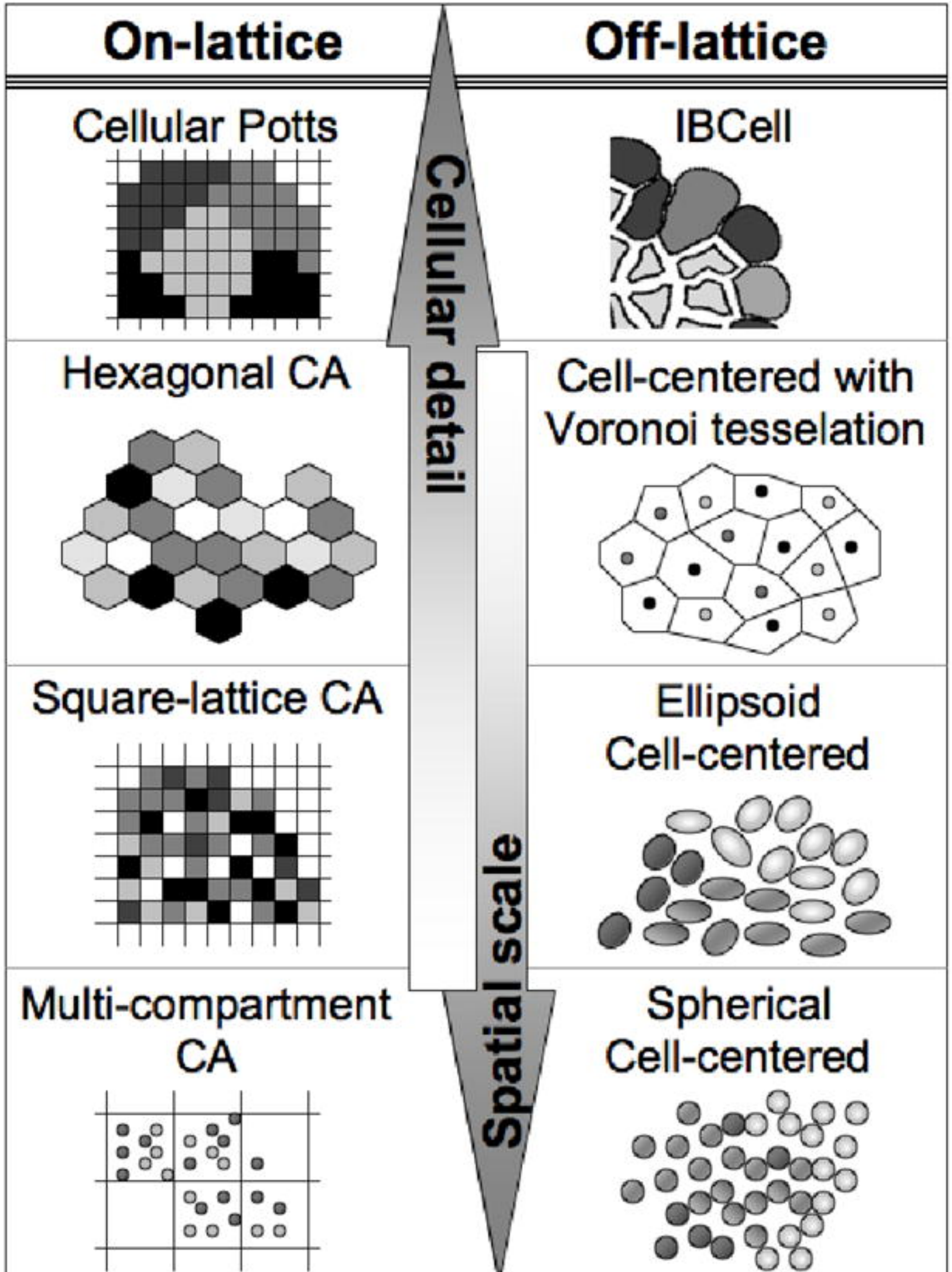


Kim & Friedman - https://www.ncbi.nlm.nih.gov/pubmed/23292359

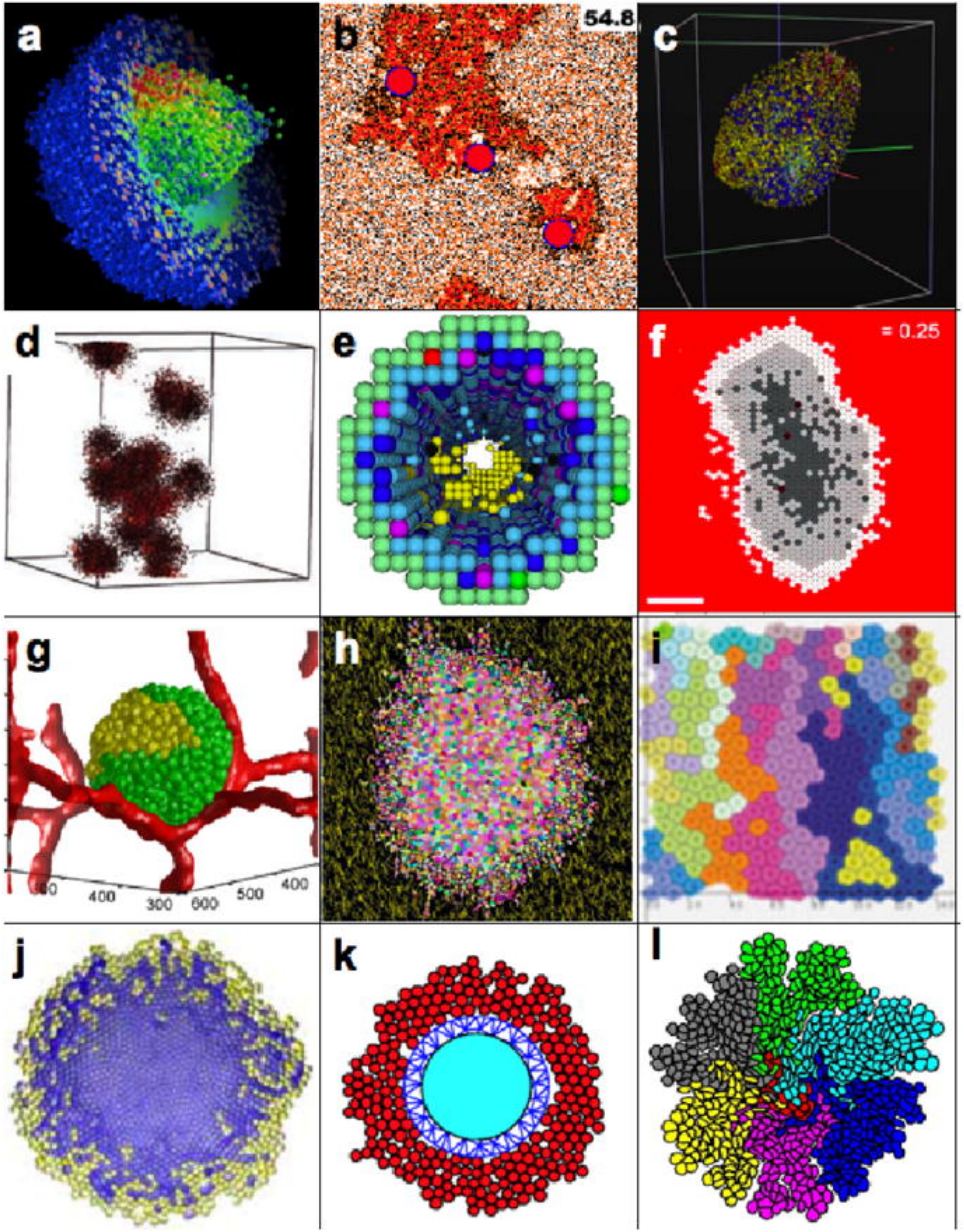


Kim & Friedman - https://www.ncbi.nlm.nih.gov/pubmed/23292359


(A) t=0.0 day
(B) t=2.5 days
(C) t=4.2 days
(D) t=5.0 days
(E) t=6.4 days
(F) t=6.7 days
(G) t=6.7 days
S
D
$S_u > S_l$
(H) Tumor Growth
Population
Time (h)
Uniform (F)
Half stiff (G)
(I) Tumor Growth
Nonuniform (G)
(J)
Tumor population
Uniform, upper
Nonuniform, upper
Uniform, lower
Nonuniform, lower
(K)
Population ratio (%)
Upper section
Lower section



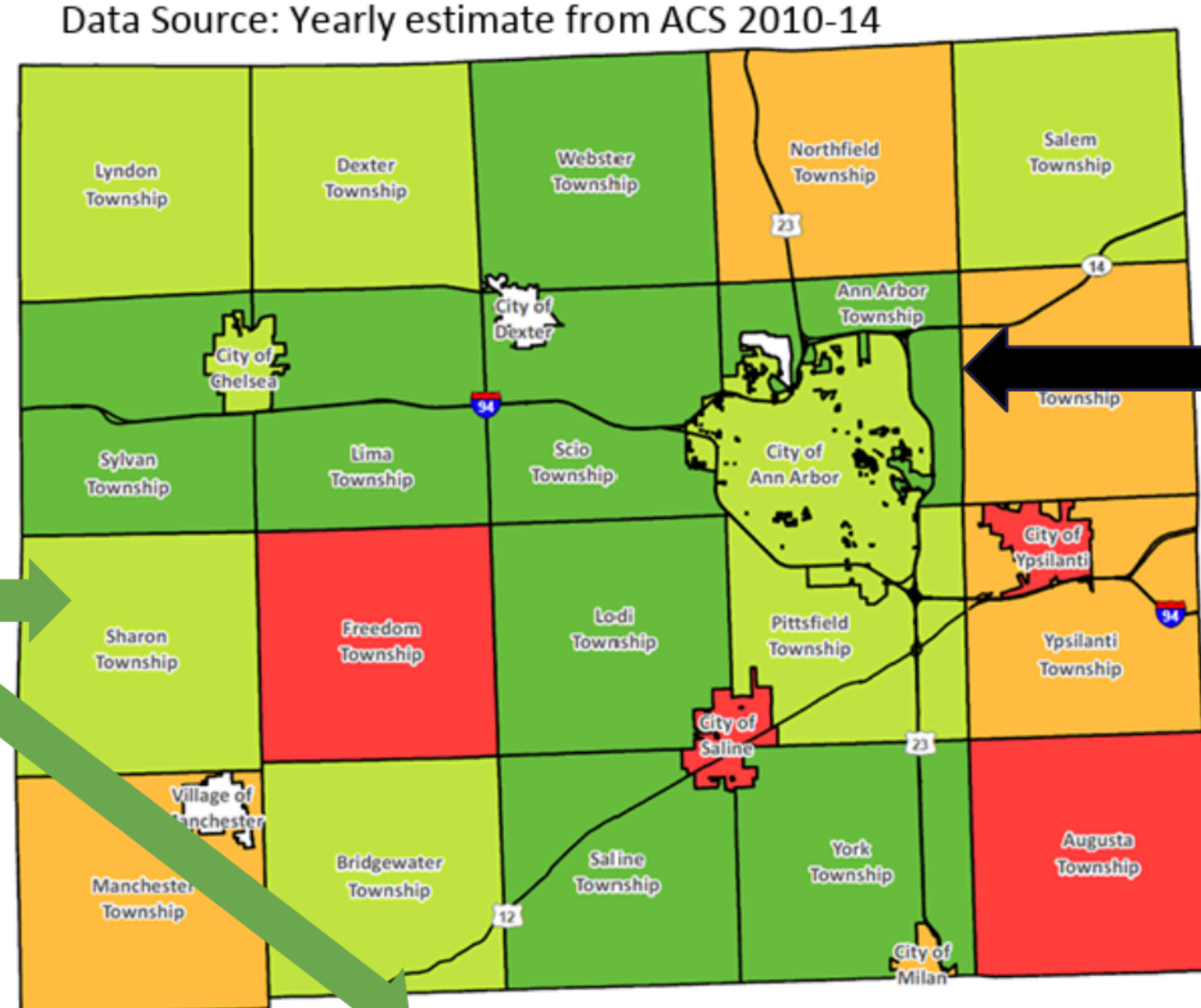
Rejniak & Anderson - https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3057876/


a
b
54.8
c
d
e
f
= 0.25
g
400
300
600
500
400
h
i
j
k
l

A little bit about mapping & GIS more generally

- Making maps requires two types of data:

Percent of individuals 65+ yrs living below 200% of FPL
Washtenaw County
Data Source: Yearly estimate from ACS 2010-14



<12% 12% to <19% 19% to <26% >=26%

Note: Jurisdictions with no color had too few people for accurate ACS estimates.

The metric / data you want to present

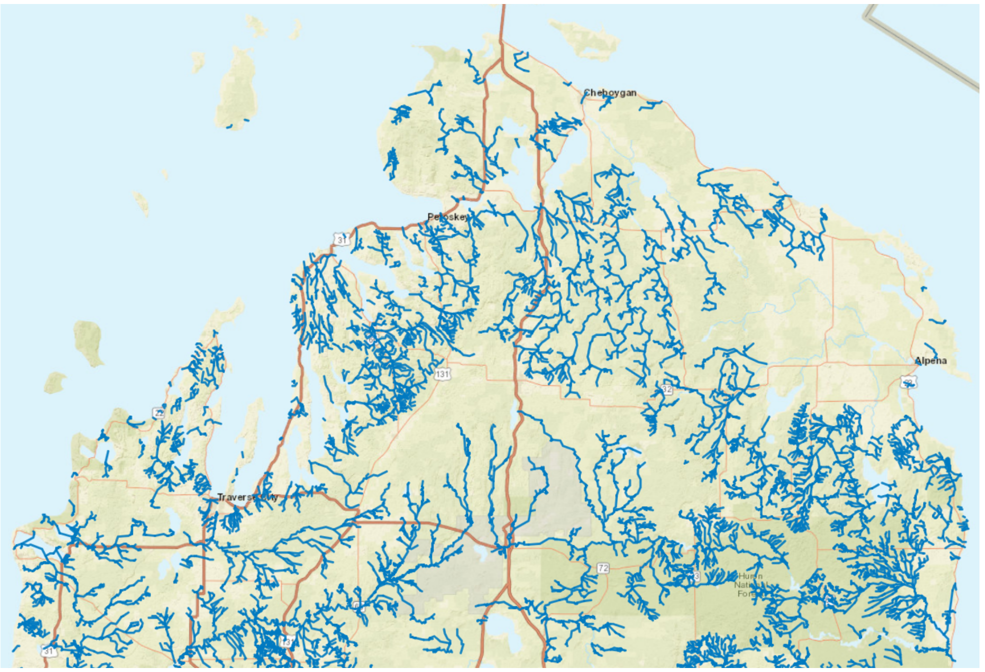
The physical geography outlines

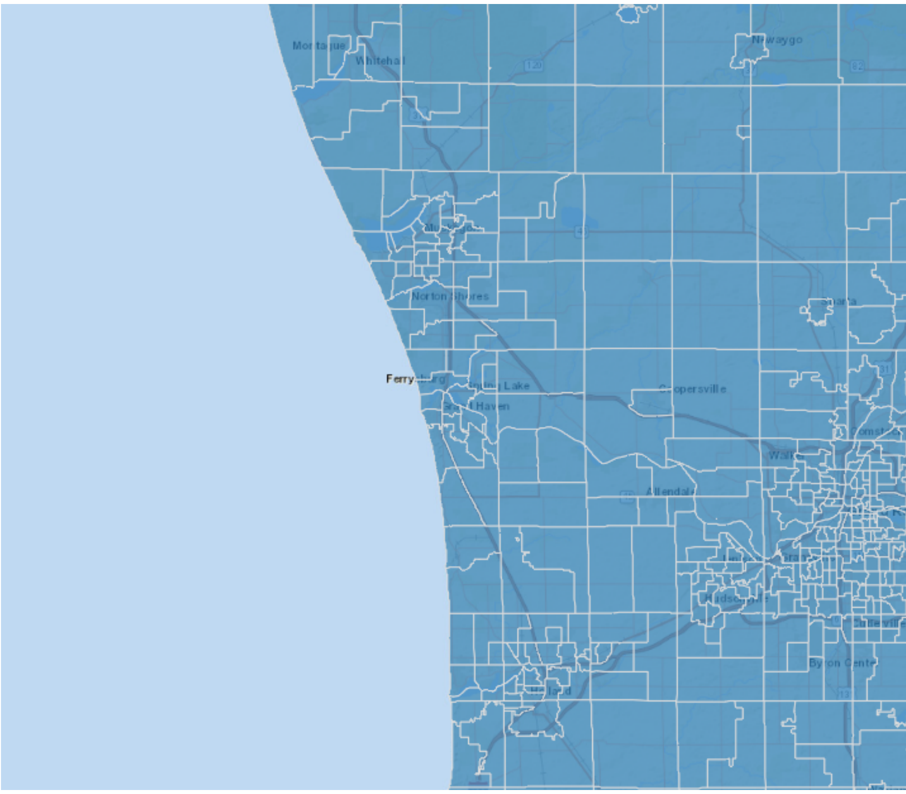
https://content.civicplus.com/api/assets/5a437802-b391-40bc-a405-4b3111130036?cache=1800

Shape files

- The shapefile format stores the geometry as geometric shapes like points, lines, and polygons

- These shapes, together with data attributes that are linked to each shape, create the representation of the geographic data



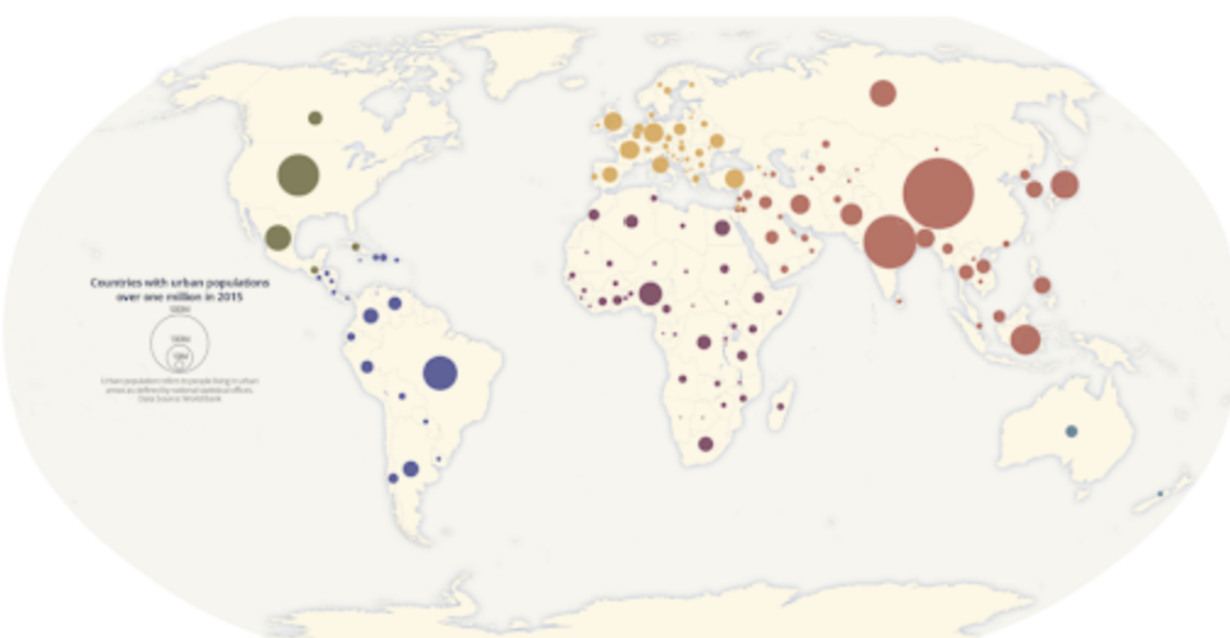


Shape files

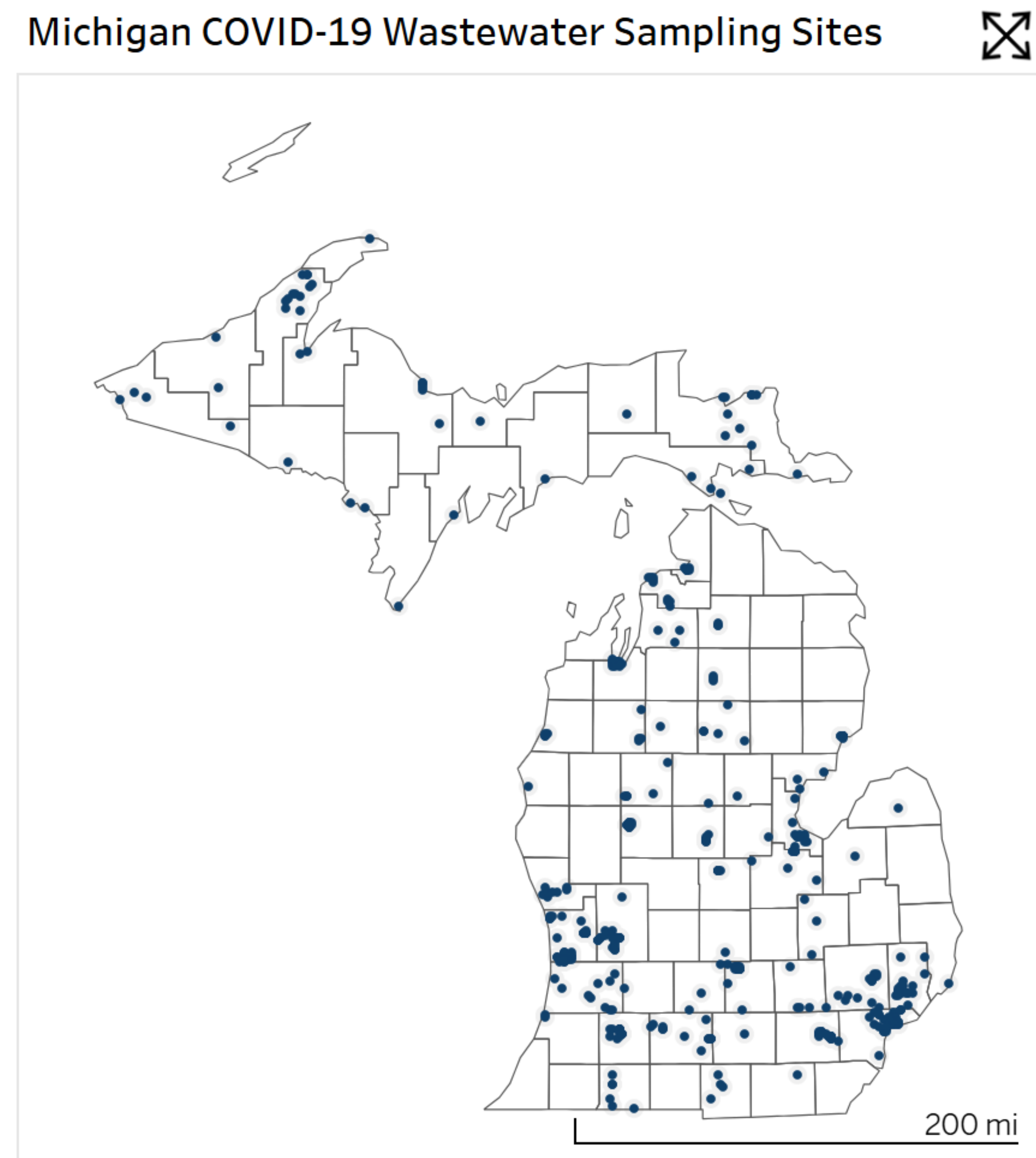
- Generally, these files are very large, as they often encode a lot of information
- Common Sources:
  - Census.gov: https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html
  - Michigan GIS Open Data: https://gis-michigan.opendata.arcgis.com/
- (can also make your own)

Types of Maps: Point Map

Point maps are used to indicate exact locations (or central locations) for particular events.



Graduated Symbol Map

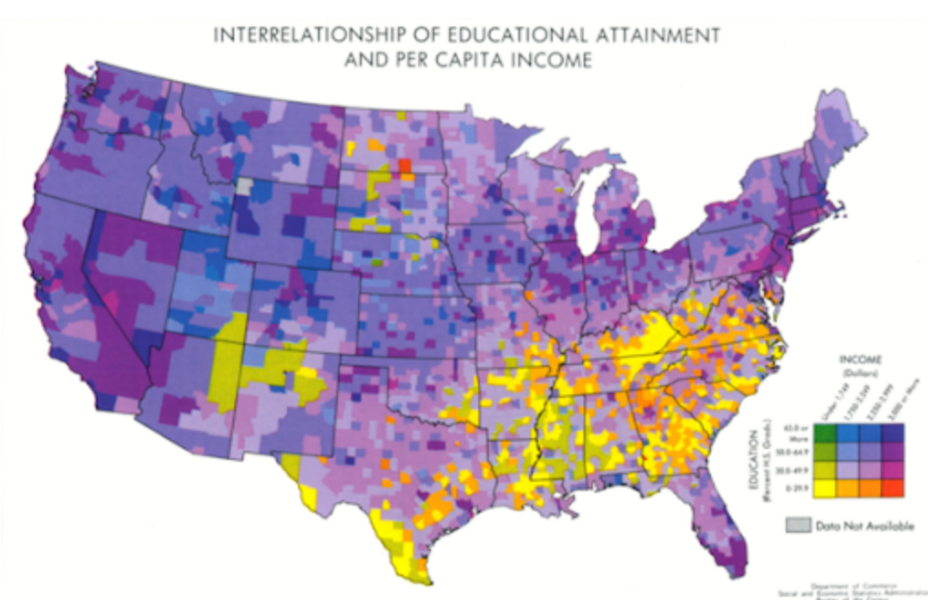


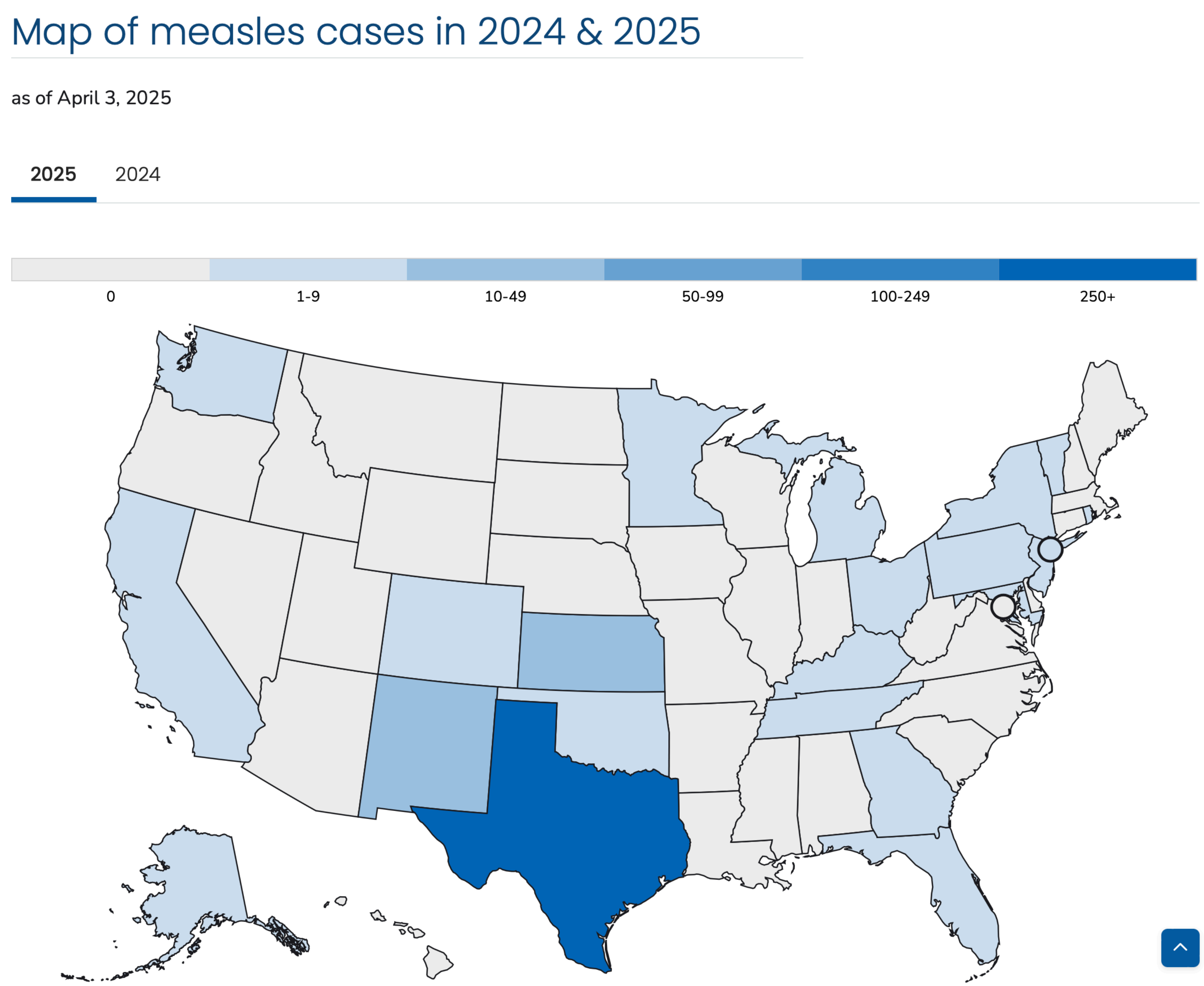
Note: This map displays sampling sites that have ever participated in this wastewater monitoring effort in Michigan since 2020. Both active and inactive sites are included.

https://www.michigan.gov/coronavirus/stats/wastewater-surveillance/wastewater-surveillance-for-covid-19/dashboard

Types of Maps: Choropleth

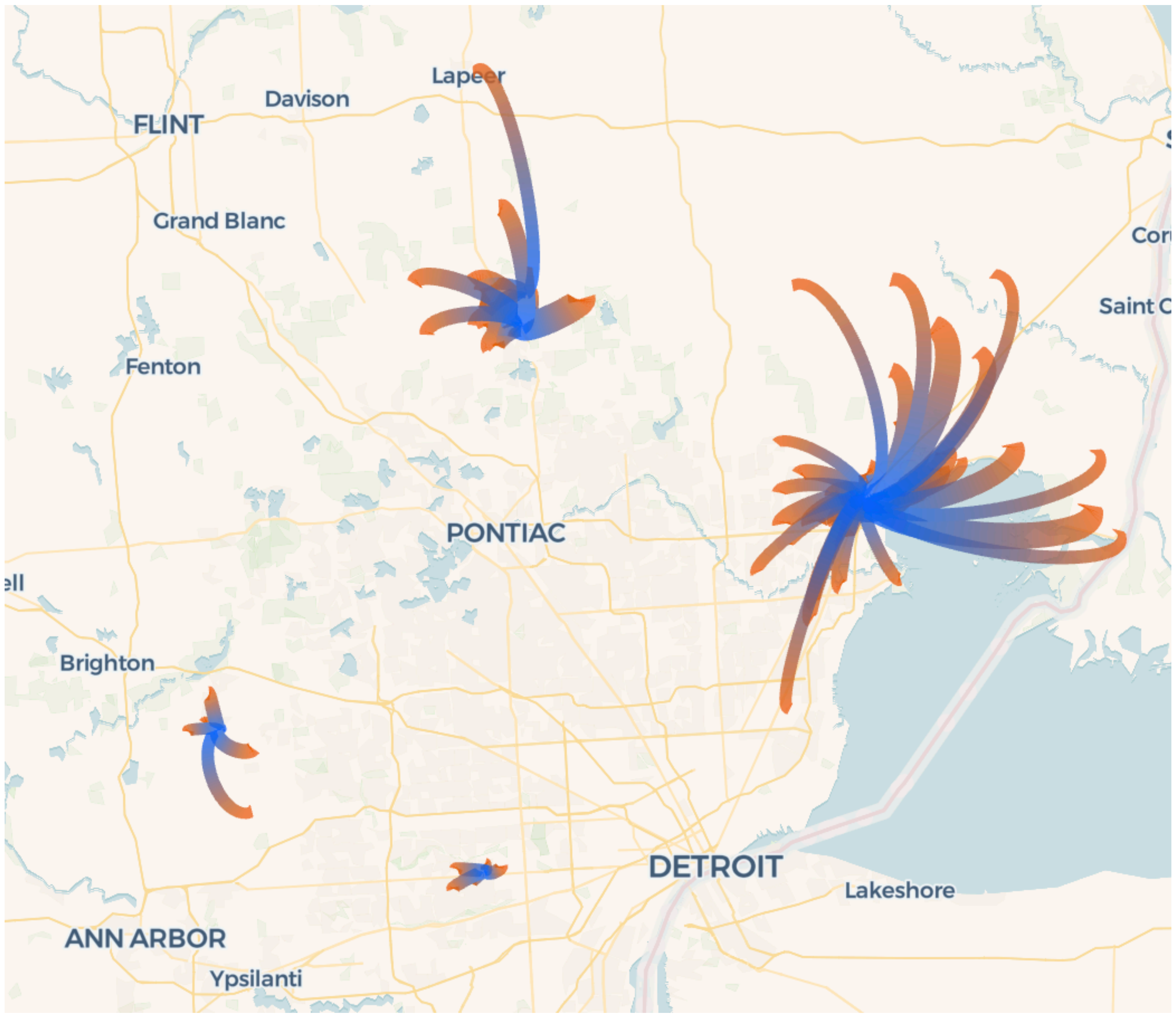
Geographic areas are outlined and filled with a color that represents an aggregate summary metric for the area

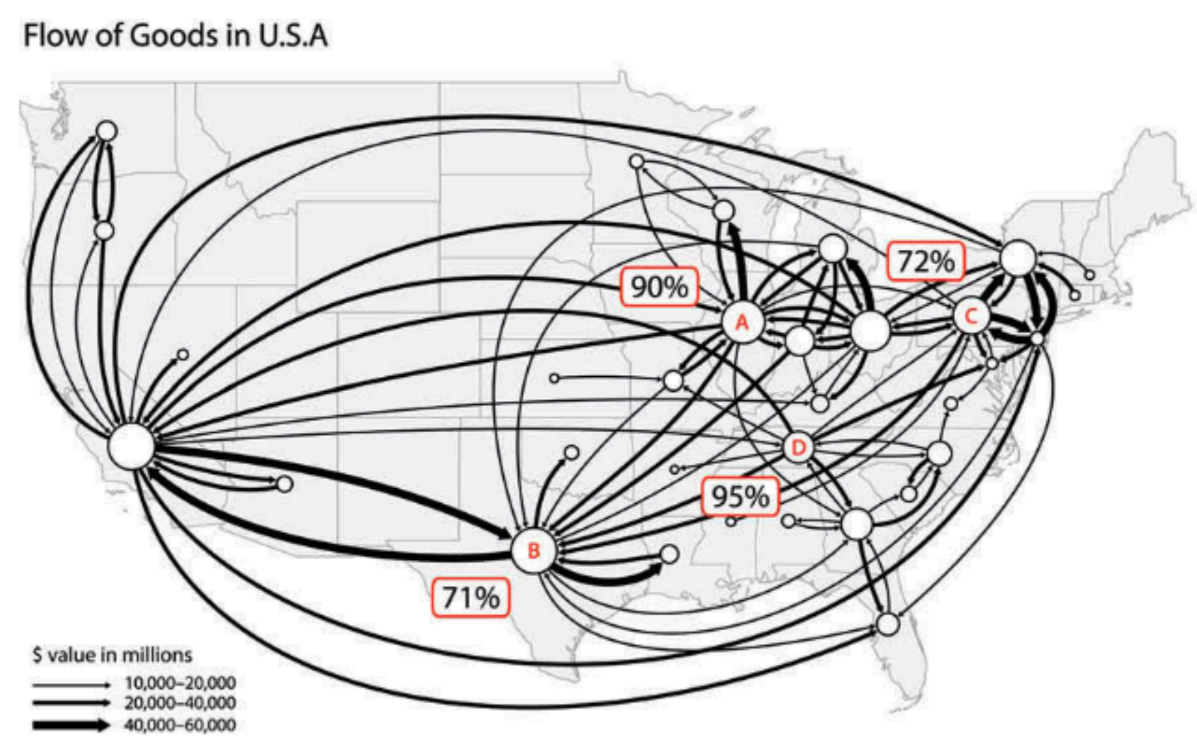




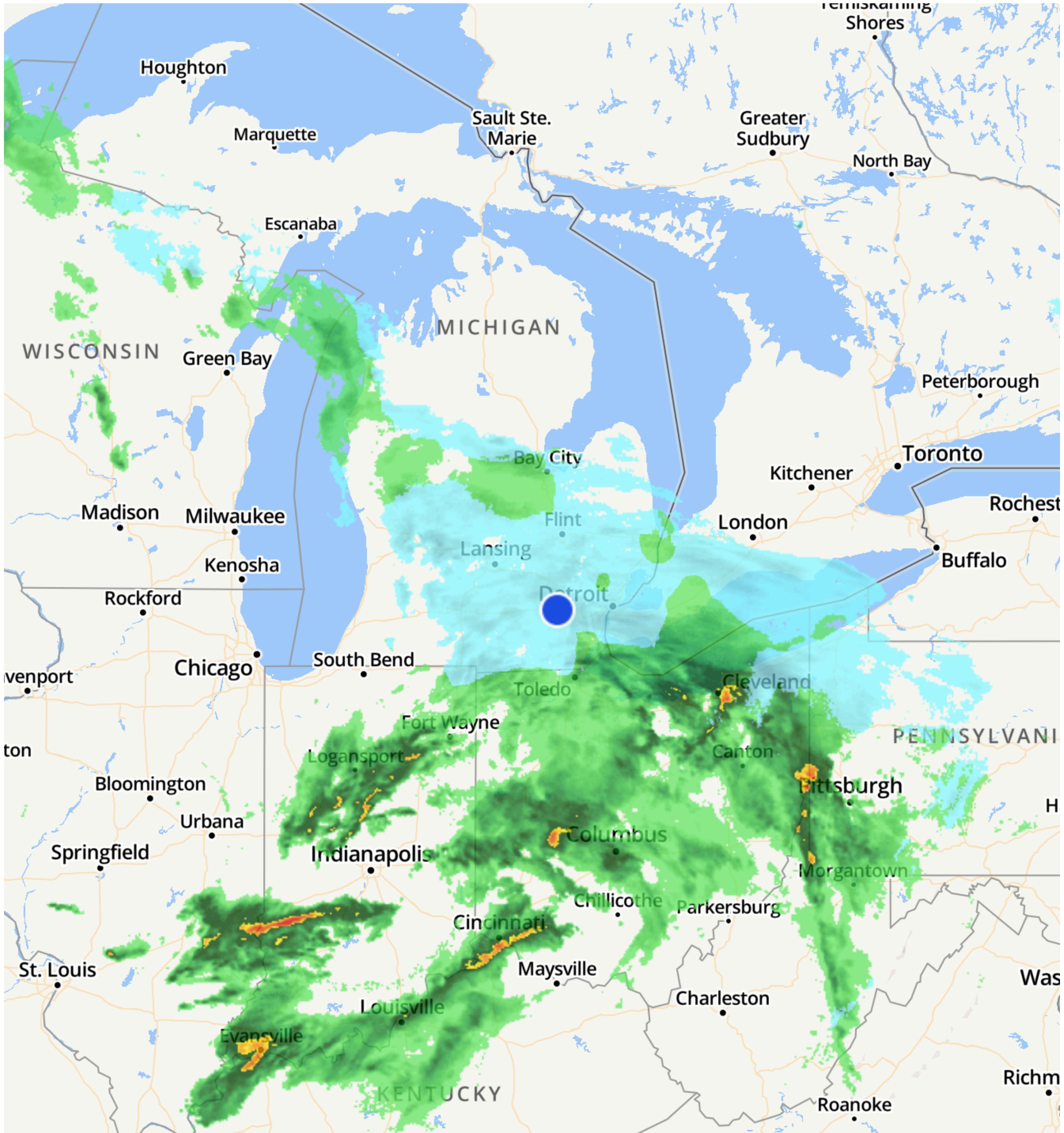
https://www.cdc.gov/measles/data-research/index.html

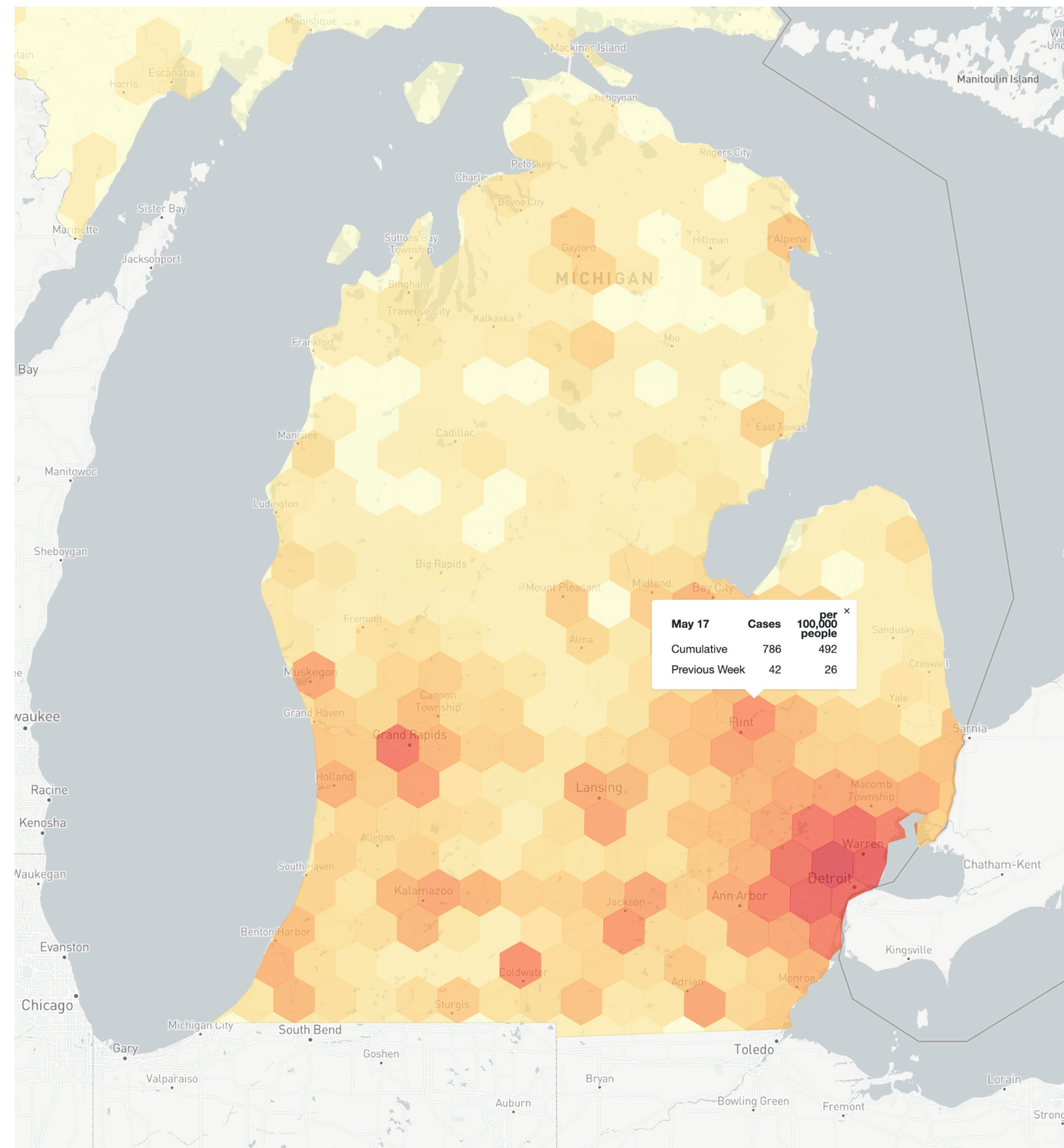
Network and flow maps



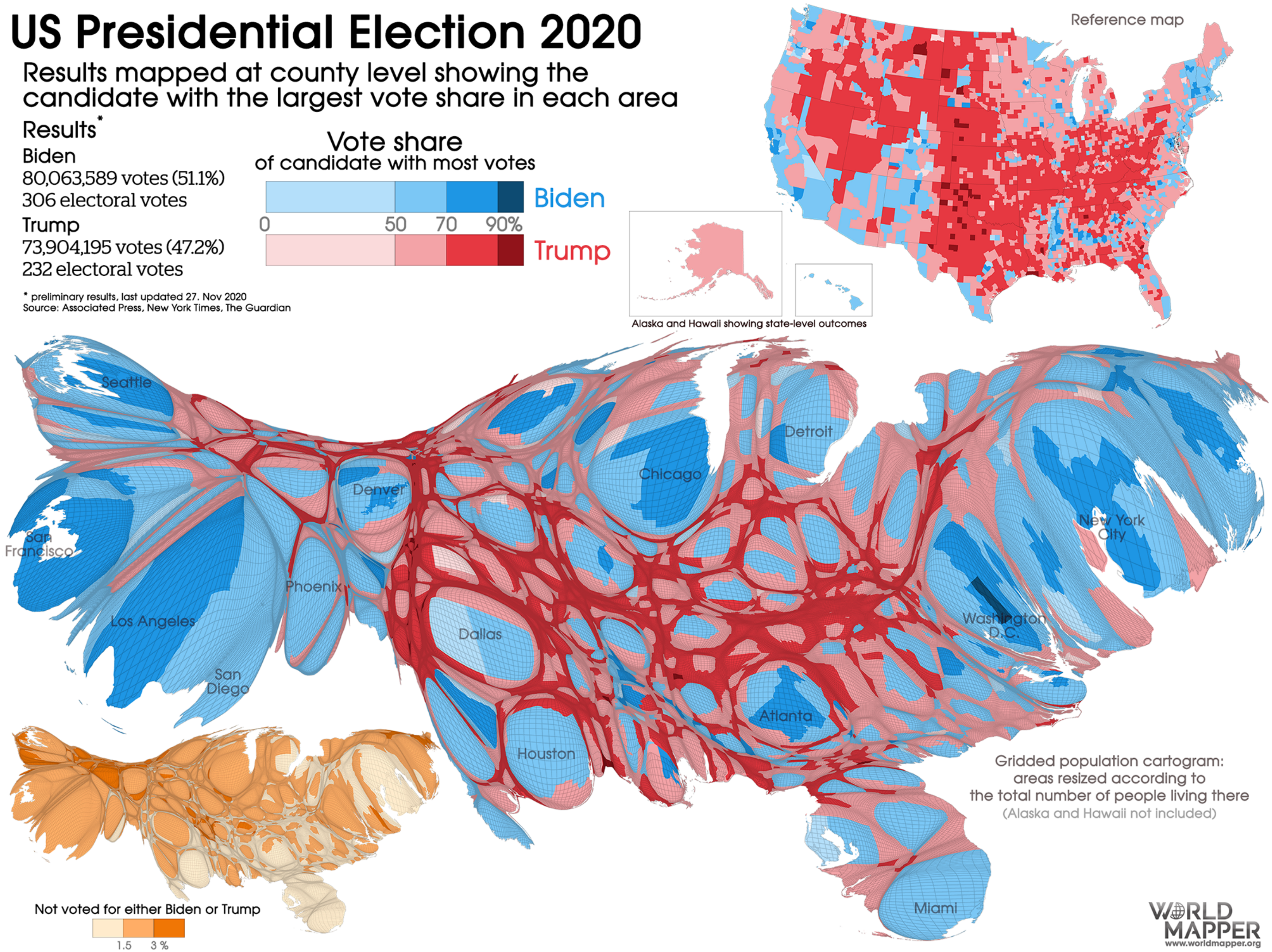


Heat maps & hexbin maps





Cartograms


US Presidential Election 2020
Results mapped at county level showing the candidate with the largest vote share in each area
Results*
Biden
80,063,589 votes (51.1%)
306 electoral votes
Trump
73,904,195 votes (47.2%)
232 electoral votes
* preliminary results, last updated 27. Nov 2020
Source: Associated Press, New York Times, The Guardian
Vote share
of candidate with most votes
0
50
70
90%
Biden
Trump
Alaska and Hawaii showing state-level outcomes
Reference map
Seattle
Denver
Chicago
Detroit
San Francisco
Phoenix
Los Angeles
San Diego
Dallas
Houston
Atlanta
New York City
Washington D.C.
Miami
Gridded population cartogram:
areas resized according to
the total number of people living there
(Alaska and Hawaii not included)
Not voted for either Biden or Trump
1.5
3 %
WORLD MAPPER
www.worldmapper.org

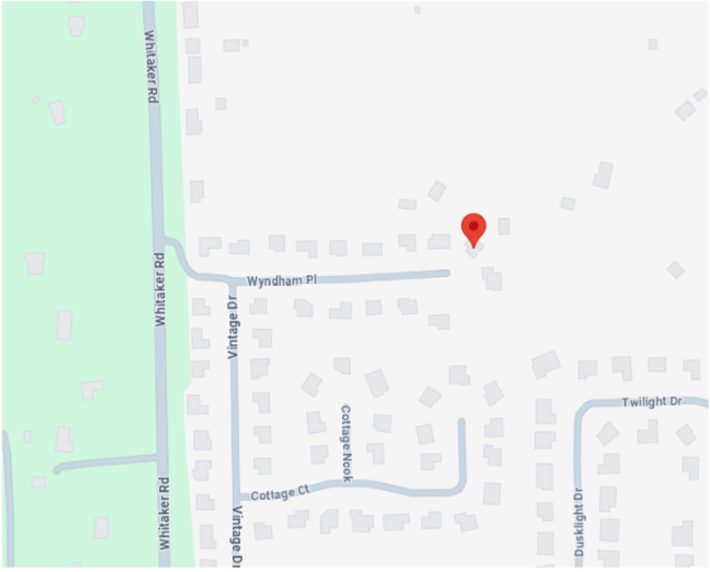
Mapping package we'll use today: Folium/leaflet

- Can generate a wide range of map types and base map layers
- Interactive maps
- Folium is a python wrapper/package based on the javascript leaflet library

Small note about geocoding security

- Geocoding: converting from address to lat-long (and sometimes need to do the reverse)
- Usually requires sending the address to a service (google maps, whatever else)
- This means sharing that data with an outside service, which can be complex from a identifying/security perspective (e.g. geocoding a list of cases)

1234 Street
Town, State 56789



(42.785823, -83.772496)

Let’s play with an example!

- Basic intro to mapping with Folium
  - https://colab.research.google.com/drive/1a0Ieo811QtyEImImO15I3JjqbNRSiU6f?usp=sharing
- Predator prey model but now predators search for bubble tea in Ann Arbor:
  - https://colab.research.google.com/drive/1URlq_NWnXBNV0nnm7A3BxiCyd2f8kmjG?authuser=1#scrollTo=jp3zcRX8IXJA