ODD protocol

The model description follows the ODD (Overview, Design concepts, Details) protocol for describing individual- and agent-based models (Grimm et al. 2006, 2010).

# 1. Purpose

This agent-based model (ABM) explores the relationship between the ethnic composition of a residential area and the spatial variation in opinions on ethnically salient topics (such as immigration policies). The ABM builds on three principles:

1. There is geographical variation in the ethnic composition of a residential area. In the ABM, the ethnic composition and spatial distribution of the agent population is calibrated on twelve residential districts of Rotterdam, and specifically on the spatial distribution of non-western minorities within these districts.
2. The frequency (or likelihood) of interaction decays with distance. In other words, spatial proximity fosters interaction and thus increases the potential for opinion change. We model this by assuming that the probability that two agents interact is function of their distance in the district. The ABM explores how the strength of this distance-decay affects the system.
3. Whether one’s interaction partner belongs to the ethnic ingroup or outgroup moderates the effect of the interaction on one’s opinion change. In the ABM this principle is reflected in the choice of the social influence model that guides the opinion change of interacting agents. The social influence model is here assumed to be one of *repulsive influence*, or *RI-model* for short (Feliciani, Flache, & Tolsma, 2017; Flache, 2019). The RI-model assumes indeed that the interaction between agents from different ethnic groups is somewhat more likely to increase disagreement between them, than interactions between same-group agents.

# 2. Entities, state variables, and scales

Agents (simulated district residents) are the only entities in this ABM. Follows a list of agent attributes and global variables.

## Agents’ attributes

* Geographic location, expressed as WGS 84 coordinates.
* Group. This is a dichotomous variable identifying an agent’s ethnic membership. It can take values 1 (agent with a non-western background) or -1 (native or otherwise western background).
* Opinion: a continuous variable with range [-1,+1].

## Global variables:

* Time (discrete steps);
* Neighborhood size: not to be confused with the neighborhood considered during the segregation procedure. This is the size of the set of closest agents (based on an Euclidean distance);
* *H*: during an interaction between two agents, this parameter defines the relative importance of the difference in agents’ group belonging and the difference in their opinion in in determining the weight of the interaction;
* *M*: This parameter has range [0, 1]. during an interaction between two agents, *M* defines the relative strength of the two mechanisms (negative influence and persuasive arguments) in determining how agents update their opinion. In other words, this parameter serves as a switch between the two mechanisms;
* *S*: *S* ∈ ℕ and *S* ≥ 2.  Capacity of agents’ memory;
* Interaction noise: Number of interactions that, at each time point, take place between non-neighboring agents.

# 3. Process overview and scheduling

The simulation starts with the setup procedure. This procedure has two steps: first, it segregates agents by group identification according to a Schelling-like segregation submodel. Second, it computes each agent’s vector of neighbors (neighborhood).

Once the setup procedure is over, the actual model run can begin. For each time step, the run procedure randomly selects from every agent’s neighborhood an interaction partner *j*; then, interactions are carried out.

Interactions between a focal agent *i* and her interaction partner *j* consist of three sequential steps (submodels): update of weight, update of *i*’sraw opinion change, and update of *i*’s opinion.

In case the model is run under the assumption that there is interaction noise, then new interactions are carried out, as many as imposed by the quantity of interaction noise. These interactions take place between focal agents *i* and interaction partners *j* randomly picked from the set of not neighboring agents.

In pseudocode, this translates to:

execute segregation procedure

compute neighborhoods

**infinite loop** ‘run‘ {

make interactions {

**for each** i **from** agentset (in random order) **do**

**set** interaction partner **as** j **to** one of neighbors (with a uniform probability)

update weight (i,j)

update raw opinion change (i,j)

update opinion (i,j)

}

**if** interaction noise > 0 **do**

**set** n **to** interaction noise

**set** K **to** subset of agents of size n (chosen with a uniform probability)

**for each** k **from** K (in random order) **do**

**set** interaction partner **as** j **to** one of **not** neighbors (with a uniform probability)

update weight (i,j)

update raw opinion change (i,j)

update opinion (i,j)

**set** time **to** time + 1

}

# 4. Design concepts

## Basic principles

The model builds on two existing models of opinion formation: a model of (positive and) negative influence (Flache & Macy, 2011b; Macy et al., 2003), and a model of persuasive arguments exchange (Mäs et al., 2013; Mäs & Flache, 2013). These two models differ in their underlying sets of assumptions about individual behavior and opinion adaptation. Both the two models are capable of generating opinion polarization in a population but, theory suggests, they also make conflicting predictions about the relationship between segregation and polarization.

This model consists of a common framework for the models of negative influence and persuasive arguments to run under the same conditions. Thus, it helps understanding how their competing sets of assumptions actually vary the effects of spatial segregation on the emergence of opinion polarization. More broadly, this work contributes to the understanding of the conditions which foster or hinder the emergence of polarized opinions in a population.

Segregation is the independent variable in the explanation that this model contributes to build – hence, the central role it has in this work. Spatial segregation is modeled by means of an adaptation of the traditional Schelling model of residential segregation (1971) that will be explained later in the text.

## Emergence

Opinion polarization is the main emergent phenomenon in this model. System variables affect how polarization emerges in two ways: on the one hand, they affect the strength and direction of the relationship between segregation and polarization. On the other hand, they affect the spatial patterns of emergent opinion clusters in terms of strength of the alignment between agents’ group identification and opinion.

## Adaptation

With regard to the segregation procedure, agents adapt to the environment by looking for a position on the map which best satisfies their utility function.

With regard to the opinion dynamics, agents adapt to their environment by updating their opinion according to the rules imposed by the two processes of opinion formation. An agent’s environment is her set of neighboring agents; the environmental features which trigger the opinion update are two: neighbors’ opinion and their group belonging.

## Objectives

In the segregation procedure, agents’ objective is determined by an utility function (defined later on in the text). In the opinion dynamics, agents’ objectives are different depending on the process of opinion formation.

The process of negative influence implicitly assumes two agents’ objectives. First, to comply with the homophily principle, according to which interactions between similar individuals are more likely or more relevant than interactions between dissimilar ones. Secondly, to strive for balanced cognitions (Festinger, 1957), that is, in short, to have an opinion in line the opinion of ingroup members and opposed to the opinion of the outgroup members.

The process of persuasive arguments exchange implies agent’s objectives to comply with the homophily principle, as well as to share opinions with interaction partners by communicating arguments.

## Learning

Learning hasn’t been modeled as one of agents’ features. Agents’ adaptive trait (their opinion) varies across time solely as a function of their present opinion and of the effects that the current interaction has on that opinion. As a result, agents’ opinion development can be thought as a discrete time Markov process where only the current state affects the next one.

## Prediction

This model explores the theoretical implications of the assumptions underlying two processes of opinion formation: although this links to a better understanding of the conditions fostering (or hindering) opinion polarization, actual predictions on the effects of segregation on polarization in real world settings still lie beyond the scope of this model.

## Sensing

In the segregation procedure, agent’s sense of the environment is limited to the group composition in their local portion of the map (defined by the radius *r*).

In the opinion dynamics, agents sense their neighbors’ group belonging and opinion.

## Interaction

Interactions are modeled as dyadic (between pairs of neighbors). During an interaction, agents update their opinion differently depending on the process of opinion formation. In the case of the negative influence process, agents’ interactions consist in a comparison between the group belonging and opinion of the two agents: if they are similar, they update their opinion in a way to average their opinion (positive influence). If they are dissimilar, they update opinion so that they further diverge (negative influence).

In the case of the persuasive arguments process, the model mimics the exchange of a pro or con argument. The likelihood that the argument exchanged by an agent is a pro (or con) argument depends on the sign of the agent’s opinion: agents with positive (negative) opinion are more likely to communicate a pro (con) argument.

A detailed explanation of how interactions are modeled out is provided in the submodel section.

## Stochasticity

This model resorts to stochasticity in a number of processes. Randomness is the mean by which it generates variability in these processes (explained in detail in the submodels section):

* Schelling procedure:
  + Agents’ assignment to one of the two groups or to the buffer;
  + Agents’ choice of the location where to move among all available locations which satisfy the criteria;
* Definition of agents’ initial opinion;
* Agents’ choice of an interaction partner. The partner is picked with a uniform probability among agents’ neighbors (or, in case of interactions carried out as interaction noise, among agents outside the neighborhoods);
* Argument communication mechanism: here the random function is used twice: once for choosing the sign of the argument an agent drops from the memory, and once for choosing the sign of the argument communicated by the interaction partner.

## Collectives

Agents are divided into two groups of similar size: group -1 and group +1. Group belonging is the agents’ trait used by the segregation procedure for the generation of spatial group segregation.

## Observation

The model computes and (optionally) outputs outcome measures once every 10 time steps, starting from time 0. These measures are:

* Dissimilarity (or ‘concentration’) index *D* by Massey and Denton (1988). This index quantifies the level of segregation generated by the segregation procedure;
* Count of agents ‘on a border’ - these are the agents who lie on the boundary of a group cluster (in other words, the set of agents who have an outgroup member in their neighborhood);
* Count of agents ‘close to a border’ – agents who have an agent ‘on a border’ in their neighborhood;
* Polarization index. This is the variance in the distribution of the differences in opinion between agents, and represents the main outcome variable. In order to make the computation of this measure applicable to the large population, the model computes the polarization index on a random sample of agents (N=64, consisting in the 1% of the entire population) ;
* Opinion mean and variance:
  + In the entire population;
  + Within the two groups separately;
  + For the subset of agents ‘on a border’;
  + For the subset of agents ‘close to a border’;
* The count of extremists, where extremists are defined as those agents who share an opinion in the top or bottom 5% of the opinion scale;
* For measuring alignment of opinion and group identification, the model also computes, for a sample consisting of 1% of the population, the mean opinion differences between ingroup and between outgroup members:
  + Within neighborhoods;
  + Between the sample agents and her surrounding agents at different radial distances.

# 5. Initialization

Model runs are independent from each other: this implies that the segregation procedure is run at the beginning of every run, and its outcomes in terms of group spatial distribution are stochastically determined.

Opinions are initialized by attributing uniformly random opinions to agents.

The choice for the values of system variables is theoretically driven.

# 6. Input data

The model does not use input data to represent time-varying processes.

# 7. Submodels

## Segregation procedure

The segregation procedure builds on the classic model of residential segregation by Schelling (1971). It differs from Schelling’s model in that agents decide whether to move to a different location based on a utility function (Zhang, 2004) defined as follows:

Where *m* is a constant factor representing the desirability of a neighborhood of only ingroup members, and *p* represents the optimal fraction of ingroup members in the neighborhood (*n*). It follows that agents enjoy the highest utility when the proportion of ingroup members equals *p*. Proportions greater than *p* may result in a lower utility, if *m*<*p*. Please note that in this procedure only, ‘neighborhood’ is the set of agents around (and comprising) the focal agent lying within *i*’s radius *r*, and should not be confused with the concept of neighborhood as used in the processes of opinion dynamics.

The segregation procedure starts by randomly defining (with a uniform probability) some agents as buffer, where the size of the buffer depends on the system variable ‘buffer size’. Then, non-buffer agents are assigned to one of the two groups (group -1 or group +1) with the same probability. At each iteration, the software defines a set of agents whose neighborhood composition is unsatisfactory (*U*<*T*). Each unsatisfied agent first scans the buffer cells in search for locations where the expected utility would be greater than *T*, thus satisfactory. If such a location exists, the agent moves to one of the satisfactory locations. If no satisfactory locations are available, the agent scans again the buffer in search for a location where the expected utility is greater than the utility she enjoys at her current location, even if the expected utility falls below the satisfaction threshold *T*. If a better location is found, the agent moves to the better location, otherwise does not move.

The segregation procedure terminates when at least one of the three following conditions is met: (1) the segregation procedure has gone through 50 iterations; (2) the segregation procedure has gone through 3 iterations without agents moving; (3) there are no unsatisfied agents left to move.

At the end of the procedure, buffer cells are assigned to group 1 with a probability equal to the proportion of neighboring cells already assigned to group 1 out of the whole neighborhood. With the complementary probability, cells are assigned to group -1.

## Computation of neighborhoods

This submodel builds for every agent her neighborhood as used by the opinion dynamics processes. The neighborhood of a focal agent *i* is built as an ordered list of all other agents (thus excluding *i*). Agents in *i*’s neighborhood are ordered by proximity, from the closest to the furthest away. The length of the list is defined by the system variable ‘ neighborhood size’.

## Update weight

Agent *i*'s weight toward her interaction partner *j* at time *t* is defined as:

The parameter *H* captures the relative importance of group identification and opinion in determining the weight *w*. With *H* always greater than zero, *w* ranges between -1 and +1. A higher weight signifies a stronger similarity between *i* and *j*, and vice versa. The highest similarity (*w*=1) occurs when *i* and *j* belong to the same group and have an identical opinion. Conversely, the highest dissimilarity (*w*=-1) is between two agents belonging to different groups and sharing opposite extreme opinions.

## Update raw opinion change

The raw opinion change is the result of both the mechanisms of negative influence and of persuasive arguments. The negative influence mechanism is a specification of the model as first formulated by Flache & Macy (2011) and Macy et al. (2003). The effect of the negative influence mechanism on *i*’s opinion at time *t* is function of *i*’s and *j*’s difference in opinion, and is weighted by *w*:

The persuasive arguments mechanism is a simplification of the analogous model as first formalized by Mäs et al. (2013) and Mäs & Flache (2013).

The effect of the persuasive arguments exchange depends agents’ memory capacity *S* (natural number greater than 1), and on the value of the arguments *a* exchanged during the interaction. Because in our model the opinion range equals 2, we define 2/*S* as the maximal change a new argument can cause in *i*’s opinion. Variable *a*, the argument *i* gets from *j*, therefore assumes values {+2/*S*, 0, -2/*S*}, causing a positive, null or negative opinion change. Variable *a* depends on the outcome of two events: agent *j* picking a pro or con argument, and agent *i* dropping a pro or con argument. The probability that a pro argument gets picked from an agent’s memory is

Conversely, the probability that an agent picks a negative argument is

If *i* drops (forgets) the same kind of argument that *j* picks (suggests), *i*’s opinion is unaffected by the argument exchange. We name this outcome ‘ineffective argument exchange’. Conversely, if *i* drops an argument of a different kind than the one *j* picks, then *i*’s opinion is going to change according to the kind of argument suggested by *j*:

The effect of the persuasive arguments is defined as:

The raw opinion change of actor *i* during and interaction with *j* at time *t* (*∆oi,t*) is defined as the sum of the two mechanisms (NI and PA), whose effects is weighted by the parameter *M*. *M* functions as a switch between the two mechanisms:

It is worth noting that this equation binds *∆o* to range between -1 and +1.

## Update opinion

Interactions end with agents updating their opinion based on their previous opinion and the raw opinion change *∆o*.

Once an agent has updated her opinion, a truncating function assures that it does not exceed range [-1; 1].

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