

COVID-19 Simulator

A simulation tool of COVID-19 epidemics with
Non-Pharmaceutical Interventions, zonal restraints,
personal health habits and intermittent lockdowns

User Guide

Version 1.27

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COVID-19 Simulator Version 1.27 - User guide

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Overview

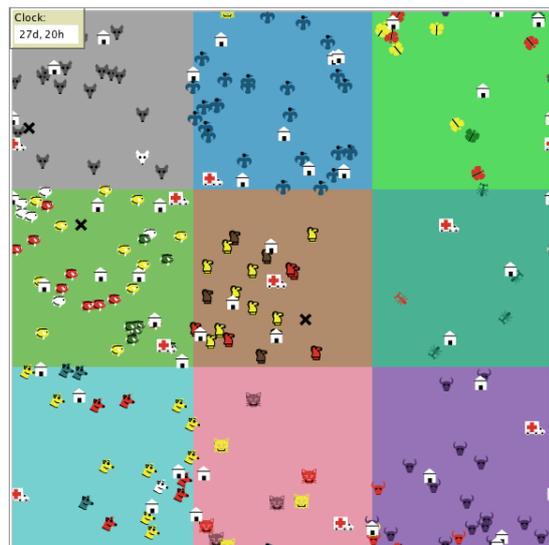
Non-Pharmaceutical Interventions (NPI) are currently the only mechanism governments can use to mitigate the impact of the COVID-19 epidemic. Similarly to the actual spread of the disease, the dynamics of the contention patterns emerging from the application of NPIs are complex and depend on interactions between people within a specific region as well as other stochastic factors associated to demographic, geographic, public policies and economical conditions.

COVID-19Simulator is a simulation tool intended to allow experimenters to simulate how the COVID-19 epidemics unfolds in a population of a toy city, and to assess how different NPI strategies affect the dynamics and impact of the disease, therefore yielding rapid insights regarding the potential application of composite interventions at different stages of the epidemic. The tool considers a number of widely-applied NPIs such as social distancing, case isolation, home quarantine, total lockdown, sentinel testing, mask wearing and a distinctive *zonal* restraint measure, requiring these interventions to be applied gradually to separated enclosed districts or zones. In addition, this new version includes the simulation of personal hygiene habits (mask-using and hand-washing) as an individual choice, plus an intermittent 3x4 or “accordion lockdown” (the lockdown is periodically enforced 3 days and lifted the following 4 days), along with the possibility of unlocking a particular zone or set of zones.

The simulation view depicts the unfold of the epidemic within a population of agents characterised by different conditions: healthy, sick, asymptomatic, tested, confirmed, critical, deadly, extinct or recovered. In addition, the tool collects and display population-wide epidemic indicators such as case fatality and lethality ratios, herd immunity, transmission rates, doubling time, and time-evolving plots showing the behaviour of the epidemics in the population subgroups as well as the effect on the health available capacity of the region.

COVID-19Simulator 1.27 has been released under GNU General Public License (GPLv3); it is available online at:

http://modelingcommons.org/browse/one_model/6423



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Chapter 1

The simulation tool

1.1 What is COVID-19 Simulator?

COVID-19 Simulator is an agent-based model to simulate the evolution of the COVID-19 epidemics and the mitigation impact of Non-Pharmaceutical Interventions (NPI) within a population of an artificial city. NPIs are the mechanisms that public health offices around the world are using to attempt to restraint the spread of the virus.

We consider a number of NPIs, including social distancing, case isolation, home quarantine, total lockdown, sentinel testing, mask protection and a proposed zonal restriction where these interventions can be applied to separated districts or zones of the city. The effect of these strategies are measured in terms of morbidity, mortality, lethality -infection fatality rate (IFR) and case fatality rate (CFR)-, doubling time, reproduction number and plots of infection, recovery and death during the simulation timeline. The main purpose of the tool is to let modelers assess which NPIs or combination of NPIs can help flattening or crushing the curve of spread of the disease (mitigate or suppress, respectively), and the effects on the corresponding epidemics indicators.

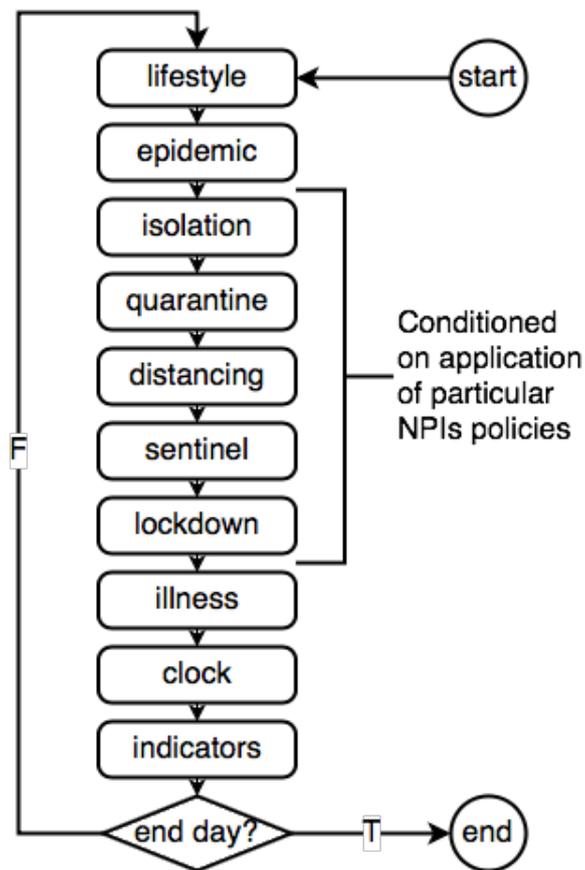
1.2 How it works

The model implements the NPIs within the epidemic SIRE+CARDS model (see [1] for further details) as well as the agent behaviour rules. We build upon the compartmental SIRE epidemic framework (Susceptible-Infectious-Recovered-Extinct), but we regarded the Infectious compartment as an extended-state consisting of a number of conditions: Confirmed or not (indicating the patient will remain isolated), Risky or not (meaning predisposition to develop severe or critical disease), Asymptomatic or not (meaning patient is unaware of being a virus carrier), Severe or not (meaning it requires to be hospitalised to avoid dead), and Deadly or not (indicating the patient requires Intensive Care Unit -ICU- assistance). The details of event transition rules and condition activation are described in [1].

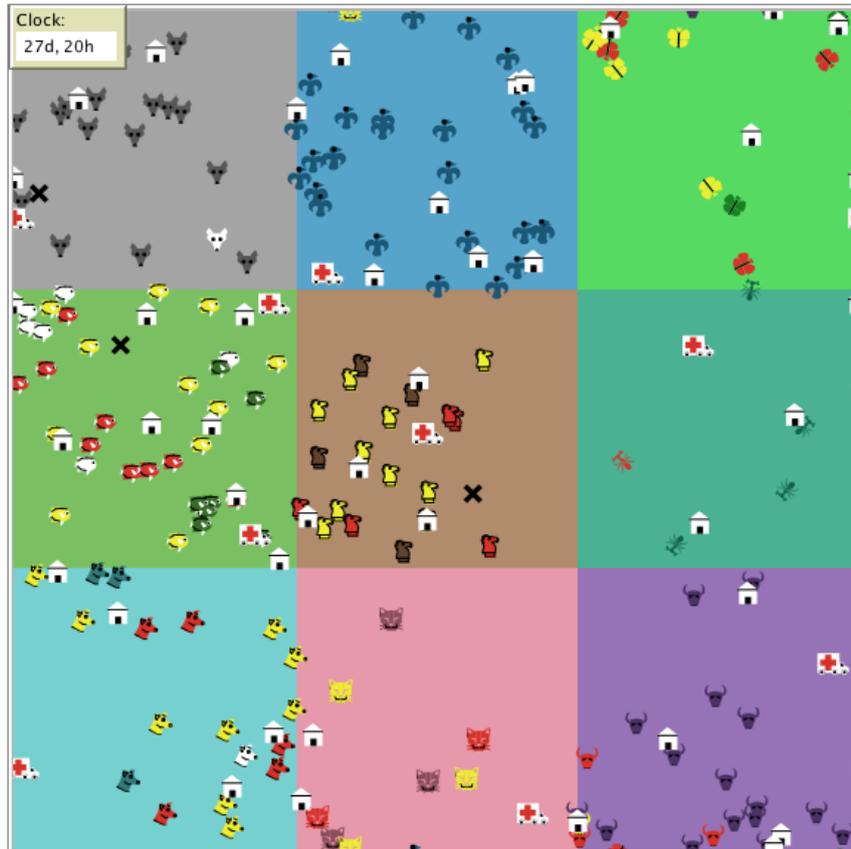
The simulation tracks an individual disease path for every agent, from susceptible to recovery or death, according to the SIRE+CARDS epidemic model aforementioned. Each agent is assigned a daily routine consisting of going outdoors and returning home with a commuting distance range randomly chosen from 25, 50, 100, 200 unit steps; the

actual route the agent follows varies slightly due to random fluctuations in his orientation. In addition the length of each step can be set as a global parameter between 0.1 and 1 units. Similarly, the day length can be defined with a given number of ticks in the range between 600 and 2400.

Individuals interact randomly with other agents around. Virus transmission occurs due to proximity of an infectious agent with other susceptible agent within a spatial radius of 0.5 units; the chance of contagion depends on what mask protection intervention is applied. On recovery from the disease, individuals acquire immunity to the virus so they cannot be re-infected. In this model all deaths are considered to be caused by COVID-19. The flow of events applied to each agent at each time step are: lifestyle, epidemic, isolation, quarantine, distancing, sentinel, lockdown, illness, clock and indicators are shown in the flowchart below (see code and [1] for additional details).

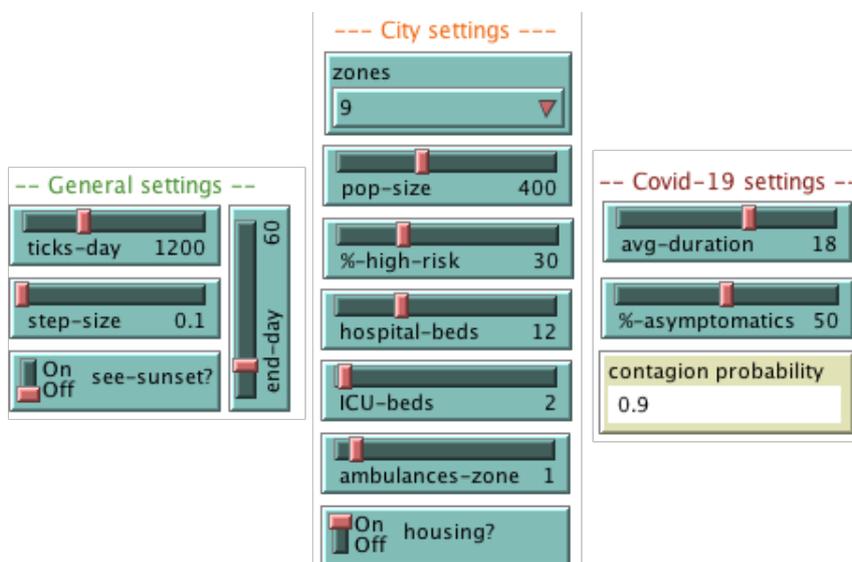


In the simulation view area, agents are represented with different shapes according to the zone where they reside. The color of the agent represents its extended state (healthy: same color as zone ground; immune: white; sick: red or yellow if asymptomatic; dead: black X). Special agents intended to implement some of the NPIs such as households for home-quarantine and ambulances for sentinel-testing can also be seen. A screenshot of the view area is shown next.



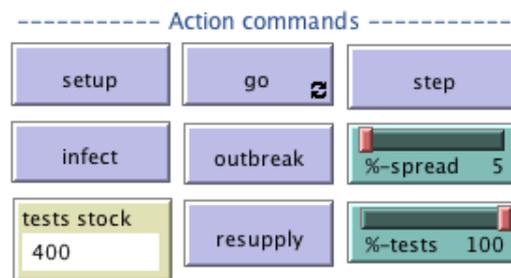
1.3 How to use it

The control panel is organised in sections related to general, city and COVID-19 settings, monitors of epidemic indicators, parameters, action commands to execute the simulation, and a dedicated section for NPI activation with their corresponding parameters. The setup panel is shown below.

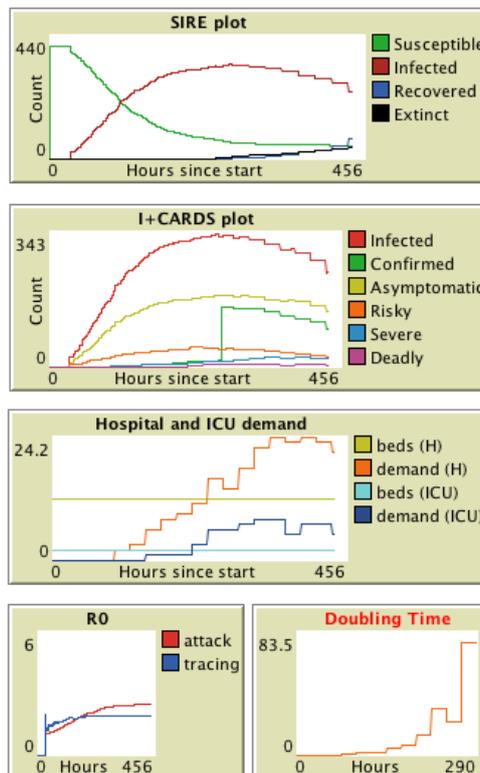


A typical setup for a simulation run is: POP-SIZE=400 (total number of simulated people or agents), ZONES=9 (number of residential zones), DAYS=60 (period of observation days or simulation length), %-HIGH-RISK=30 (percentage of population with co-morbidities), HOSPITAL-BEDS=12 (total number of hospital beds available), ICU-BEDS=2 (total number of ICU beds available), AMBULANCES-ZONE=1 (number of ambulances or sentinels per zone), HOUSING?=on (show households in the view area), AVG-DURATION=18 (average day period to recover from illness), %-ASYMPTOMATIC=50 (percentage of patients showing mild or no symptoms), TICKS-DAY=1200 (number of ticks after one day elapse), STEP-SIZE=0.1 (distance each agent move every tick), END-DAY=60 (simulation timeline).

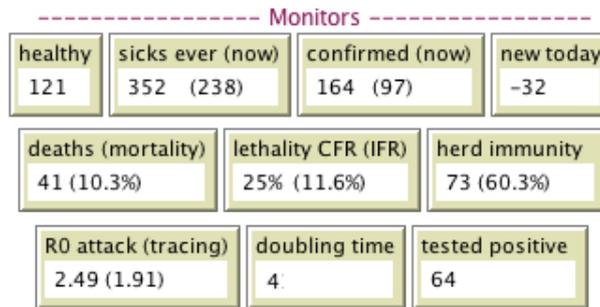
Once setup is done, activate or deactivate the NPIs you want to assess (the details of meaning and implementation of each NPI can be found in the next section), then press SETUP, then GO in the Action panel shown below:



After a few simulated hours (or ticks) you can seed a patient zero randomly (or many other, if you want) by pressing INFECT. Alternatively, using OUTBREAK you can randomly infect a percentage (%-SPREAD) of the population. Afterwards, you will be able to see the emergence of the epidemic SIRE curves in the plot panel:

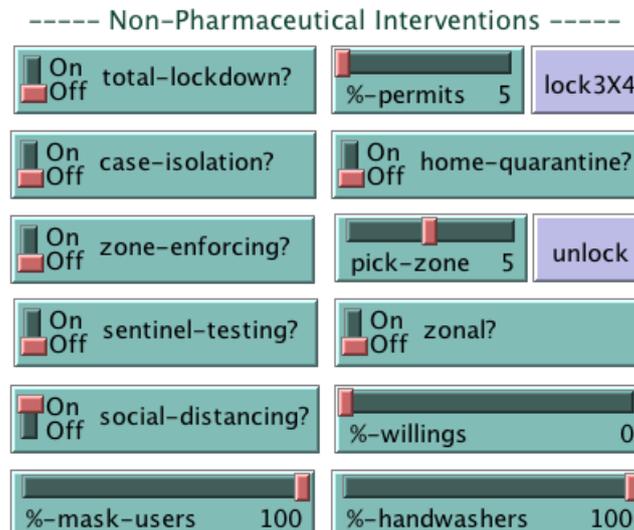


Besides, other epidemic indicators will be displayed in the monitor area, while the contagion, recover and death of people unfolds as a result of the development of the COVID-19 epidemics with such particular settings:



1.4 Non-Pharmaceutical Interventions

NPIs are health policies intended to mitigate the effects of the spread of a new virus when vaccines or medicines are not yet available. They consist of actions recommended to the public or in some cases, enforced by the government, that affect their daily life habits. During the COVID-19 pandemic, many of these action plans have been designed and deployed at a global scale. The tool provides a control panel to setup the application of these NPIs with their respective parameters. The strategies currently incorporated into the tool, are described below.



1.4.1 Social Distancing

This intervention consists of maintaining a minimum physical distance between people so as to reduce the number of close interactions between infected and healthy individuals, slowing down the speed of transmission and eventual deaths. In the tool, this intervention can be set on or off with the SOCIAL-DISTANCING? switch, whereas the actual amount of people willing to comply with the intervention can be defined with a parameter %-WILLINGS between 10 and 100%.

1.4.2 Case Isolation

This intervention consists of confining in an enclosed facility (home) either positive tested people or sufficiently symptomatic patients that self-isolate, until they recover from the disease. In the tool, this intervention can be set on or off with the CASE-ISOLATION? switch.

1.4.3 Home Quarantine

This intervention consists of confinement of relatives or housemates living in the same household of isolated cases, during their recovery. It is assumed that quarantined healthy people in the household must observe strict safety protocols to avoid contagion from the isolated case. In the tool, this intervention can be set on or off with the HOME-QUARANTINE? switch.

1.4.4 Total Lockdown

This intervention enforces a stay-at-home policy due to partial shutdown of economy. Only some people are authorised to move around to fulfil basic needs or to support essential services. In the tool, this intervention can be set on or off with the TOTAL-LOCKDOWN? switch plus a percentage %-PERMITS of mobility permits between 5 and 95%.

1.4.5 Zonal Enforcement

This intervention assumes that the artificial city can be divided in different districts (or zones), and then recommends to restrict movement of residents to their respective zones only. In other words, it enforces border closures between districts. The other NPIs can be applied localised to each zone. In addition, the model enables applying a novel NPI consisting of a total lockdown to the entire city with the option of gradually lifting of the curfew by individual zones. In the tool, this intervention can be set on or off with the ZONE-ENFORCING? switch; besides, it provides a command to unlock one zone at a time (UNLOCK-ZONE).

1.4.6 Sentinel Testing

This intervention consists of running health campaigns performing mass testing at random locations in order to detect not isolated or unconfirmed cases of either symptomatic or asymptomatic carriers. Persons whose test result positive are isolated immediately. In the tool, this intervention can be set on or off with the SENTINEL-TESTING? switch, with an option to deploy the campaigns widely or restricted to zones (ZONAL?). The stock of tests available is the parameter %-TESTS, defined as a fraction of the population between 10 and 100%. Once the campaigns run out of tests, it is possible to replenished them with a new equal supply.

1.4.7 Personal Health Habits

This intervention considers both mask-wearing and hand-washing as personal habits beneficial to prevent the contagion. The use of face masks has been recommended by the WHO to avoid spreading, or breathing in, airborne virus particles. Washing hands regularly (several times per day) has also been associated with a decreasing risk of getting infected. In the tool, this intervention is currently simulated as an individual choice, according to two parameters: estimated percentage of the population willing to wear masks (%-MASK-USERS), and estimated percentage of the population willing to wash hands regularly (%-HAND-WASHERS). While the epidemic unfolds, the risk of contagion during a single encounter of an infectious and a susceptible individual, will be modulated by the particular combination of personal health habits: 10% if both are wearing masks, 30% if carrier wears masks but susceptible do not, 50% if susceptible wears masks but carrier do not, and 90% if none wear masks. This risk will be lowered in a 30% proportion if the healthy person has acquired the habit of washing hands (e.g, if carrier wears masks but susceptible do not, the risk decreases from 30% to 9%). The actual risk for arbitrary encounters is displayed in the LAST CONTAGION RISK monitor located in the control panel.

1.5 Other distinctive features

The NPIs control panel can be used to handle their application even while the epidemic unfolds. That is, you can activate/disactivate a total lockdown at any time, and it will take effect at the 00:00 of the next simulated day. Or you can isolate or release confirmed cases immediately, by switching it on or off. Similar thing occurs with the rest of NPIs. In contrast, you should not change any other parameters (general, city, or COVID-19 settings), as they are used only before starting the simulation to setup the model.

There are two distinctive features in this model that allows the application of NPIs with a zonal scope. This means, firstly, you can restrict mobility of agents within their zone of residence; hence, you can try and see if this kind of restriction (ZONE-ENFORCING) is advantageous in flattening the curve when combined with other NPIs compared to the single application of said NPIs. Secondly, when enforcing a TOTAL-LOCKDOWN, you are able to lift this NPI in an arbitrary zone or zones using the UNLOCK-ZONE button. Again, you can see how the resulting emergencies compare to maintaining the total lockdown in the entire city. These features may yield interesting insights about alternative implementation of these measures that usually have a hard impact on the economy. Notice that TOTAL-LOCKDOWN has an associated parameter %-PERMITS to define the proportion of agents allowed to leave their households.

The SENTINEL-TESTING intervention is also useful to assess the impact of mass-test campaigns in the population. Sentinels are shown as ambulances moving around the city while testing any agent they find in their ways; again, you can restrict sentinels mobility with a zonal scope (ZONAL?) and see the difference with respect to allowing city-wide mobility. Notice that since test kits are a finite resource, the model assigns an initial stock of tests equals to the population size. When ambulances run out of tests they stop and stay still. You can of course replenish the stock for each ambulance using the RESUPPLY button to re-activate sentinels' journeys.

1.6 Try it yourself

Start-off by defining the general, city, COVID-19 and NPI settings you want to simulate in a single run (a suggested set of settings was given above, see Section 1.3). Execute the simulation to observe how the contagion spreads and how the epidemics evolve by inspecting the monitors, plots and view areas. Then try changing the NPI parameters to assess their mitigation impact by comparing with previous outputs (see Section 1.4 and also Section 1.5). If you like, start running the simulation with only one zone (choose 1 in the ZONES pull down menu); this will be equivalent to have a single district in the entire city, so agents will move around freely. Then experiment simulations with many districts or multi-zone (choose ZONES in 4, 9, 16), and try to apply ZONE-ENFORCING to see how agents mobility becomes restricted to their zones of residence.

The HOUSING? switch is used as a decoration and as a behaviour feature. When this switch is on, the tool shows households in the simulation view area and assigns agents randomly to each one with a proportion of one house per four agents approximately. When this switch is off, the household of an agent would be the patch were he/she was created randomly at the beginning of the simulation; no houses will be seen. If you try the CASE-ISOLATION or TOTAL-LOCKDOWN interventions with HOUSING? on, agents will be sent home and stay confined in their corresponding households (they will be hidden as they stay inside the house); in contrast, if HOUSING? is off, they will move to their home patch and stay quiet there, being visible and showing their shape, colour and state.

Finally, the SEE-SUNSET is a decoration feature. Try it and surprise yourself!

1.7 New features in this version

As it was mentioned before, this version includes the mask-wearing and hand-washing individual choice habits to help preventing the spread of the disease, with a more effective result when the agent observe physical distancing to other agents (try and see it!). Given that these three interventions depend mostly on individual decisions rather than government policy, it would be of great interest in the post-COVID19 scenario, to study strategies where they are combined with other interventions not affecting the mobility of the agents (such as SENTINEL-TESTING) to continue with epidemic mitigation while opening economic and social interaction.

Regarding mobility restrictions, when the TOTAL-LOCKDOWN intervention is on, in this extended model it is possible to lift it independently on the agents residing in a particular zone. For this aim, the user can choose the desired zone number with the PICK-ZONE slider and then should press the UNLOCK button. Then, the agents residing in such zone will start immediately to get out of their households and move freely around, while the rest of the population stays at home, as it can be attested in the simulation view area. When the ZONE-ENFORCING intervention is simultaneously activated, its residents will move around but only within the zone limits.

In addition, this new version enables the application of the TOTAL-LOCKDOWN intervention with an intermittent 3x4 schedule (the so called "accordion" scheme), where the mobility restriction is applied adhering to a 7-day loop consisting of enforcing stay-at-home order during 3 consecutive days, and lifting the rule the remaining 4 days.

The motivation of the 3x4 strategy is intended to ameliorate the negative impact of shutting down economy due to indefinite lockdowns. To apply the accordion intervention, the user can press the LOCK3x4 button to activate/inactivate this scheme; when activated, a "3x4 ON" sign will be displayed in the bottom-left corner of the simulation view area. We remark that once activated, this intervention, similarly to the TOTAL-LOCKDOWN, takes effect starting at zero hours of the next day (you can check it on the CLOCK monitor).

Notice that now the chance of a contagion depends on the individual decisions regarding keeping physical distance, using mask and washing hands, which varies amply depending on the habits of the two agents involved in a contagion encounter. The actual risk on a particular encounter can be seen in the LAST CONTAGION RISK monitor. You can try and see how the risks fluctuate as you change the combination of sliders of %-WILLINGS to keep personal distance, and %-MASK-USERS and %-HAND-WASHERS with values between 0 and 100 (these parameters have effect only at the beginning of the simulation, when the population is created).

Now, when the ZONE-ENFORCING and TOTAL-LOCKDOWN interventions are simultaneously been applied, it would be interesting to verify if releasing a particular single zone or a couple of them having low contagion rates, would be advantageous to facilitate mobility (and encourage economic recovering) of a group of the population without worsening too much the overall epidemic indicators of the city.

Lastly, the impact of the "accordion" LOCK3x4 intervention is evident in the epidemic SIRE+CARDS curves, which adopt a "staircase" or "chainsaw" shape with discrete rising and falling steps, corresponding to the periods of intermittent enforce/lift of the lockdown.

1.8 Extending the tool

Given the complex nature of human behaviour and virus infection, attempting to model every mechanism of the COVID-19 epidemic may prove difficult; in this tool, necessary assumptions need to be taken to simplify the representation of the agents and their interactions. We have made a few of them, as described above, so evidently there are interesting aspects that can be addressed to extend the model. We mention just some ideas here (for a more comprehensive discussion we refer the reader to [1]):

- consider virus incubation periods after infection,
- model infectiousness, aggressiveness or symptomatic severity levels,
- include age or gender structures,
- account for births or deaths due to other causes,
- expand further risk stratification for co-morbidities and age windows,
- add hubs or attractor sites (i.e. mass transport, schools, cinemas, etc.),
- incorporate explicit sites for hospitals where severe or critical patients are moved instead of staying still,

- set up daily schedules for agent routines (e.g. going forth and back to/from work, or leisure or shopping, etc.),
- measure the economical impact of NPIs (model food or money supply at a population or individual level),
- simulate cotagions not only by direct contact, but also indirect by surface contact (virus particles adhered to patches),
- implement other epidemic indicators (different estimates of R_0) or additional NPIs.
- design mechanisms allowing tendencies to develop personal health habits (like wearing masks and routinely washing hands) to emerge as consequence of changes in the psychological biases or beliefs of the agents.

1.9 References

- [1] Alvarez, L. and Rojas-Galeano, S. "Simulation of Non-Pharmaceutical Interventions on COVID- 19 with an Agent-based Model of Zonal Restraint". medRxiv pre-print 2020/06/13. doi: 10.1101/2020.06.13.20130542
<https://www.medrxiv.org/content/10.1101/2020.06.13.20130542v1>
- [2] Alvarez, L. and Rojas-Galeano, S. "Can personal health habits alone mitigate COVID-19 contagion? Insights from an ABM approach". Working paper.

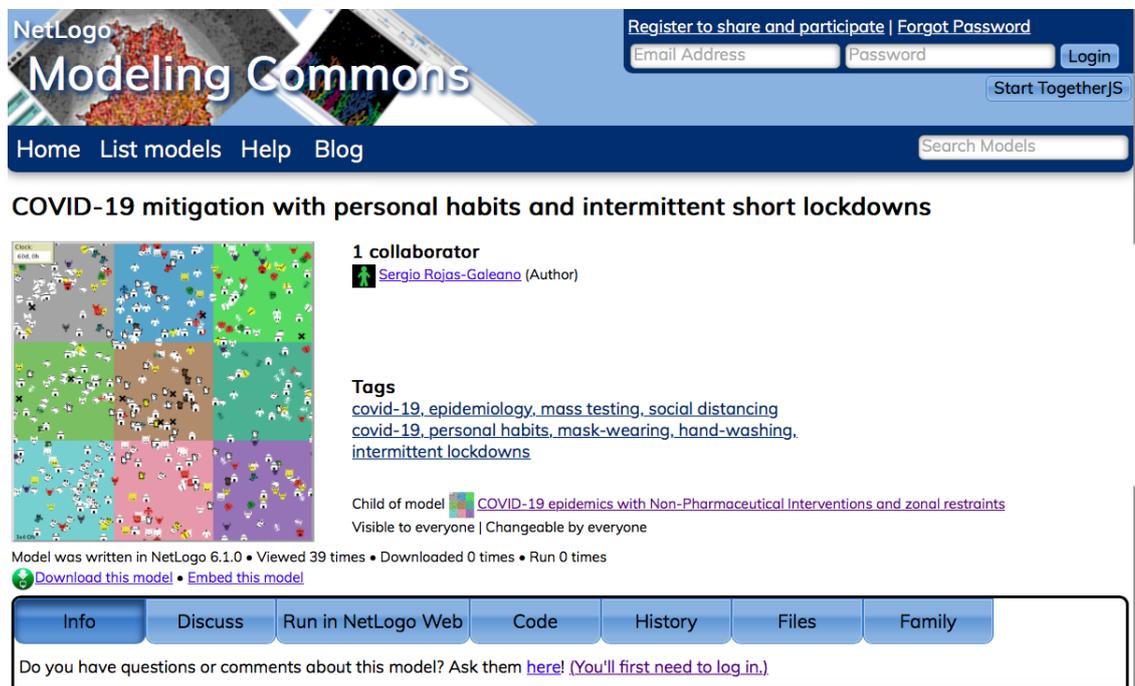
Chapter 2

Installation and execution

2.1 Online version

The easiest way of experimenting with COVID-19 Simulator is by using its online version. The software is available at the Modelling Commons website. So, you just need to follow these steps:

1. Open your favourite Internet browser and point it to the following URL:
http://modelingcommons.org/browse/one_model/6423
2. The following web page should appear:



The screenshot shows the Modelling Commons website interface. At the top, there is a navigation bar with the site logo, a search bar, and links for 'Home', 'List models', 'Help', and 'Blog'. A user login section is visible with fields for 'Email Address' and 'Password', and buttons for 'Login' and 'Start TogetherJS'. The main content area displays the model title 'COVID-19 mitigation with personal habits and intermittent short lockdowns'. Below the title is a thumbnail image of the simulation, which shows a grid of colored squares representing different zones, with small icons of people moving between them. To the right of the thumbnail, it indicates '1 collaborator' and lists the author 'Sergio Rojas-Galeano (Author)'. There is a 'Tags' section with links for 'covid-19', 'epidemiology', 'mass testing', 'social distancing', 'personal habits', 'mask-wearing', 'hand-washing', and 'intermittent lockdowns'. Below the tags, it shows the model is a 'Child of model' and provides statistics: 'Model was written in NetLogo 6.1.0 • Viewed 39 times • Downloaded 0 times • Run 0 times'. At the bottom of the model page, there is a toolbar with tabs for 'Info', 'Discuss', 'Run in NetLogo Web', 'Code', 'History', 'Files', and 'Family'. A red arrow points to the 'Run in NetLogo Web' tab.

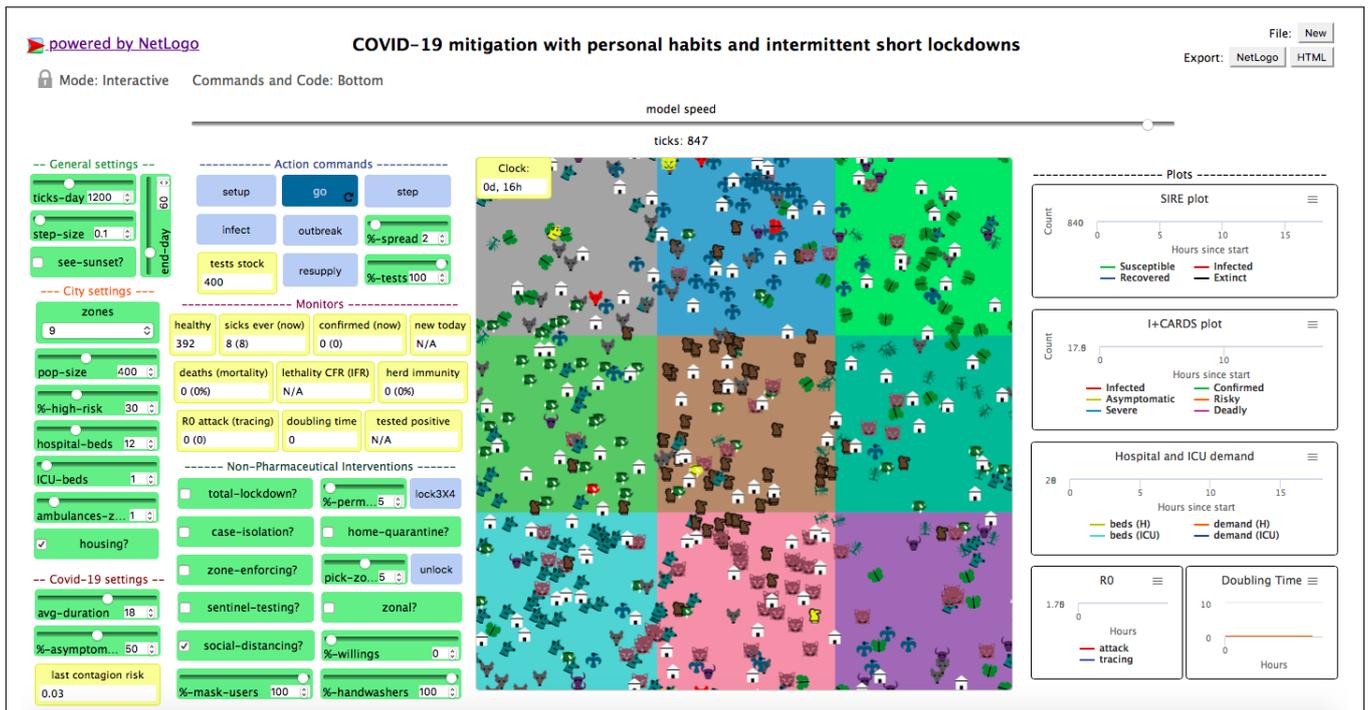
3. From the toolbar, choose the “Run in Netlogo Web” tab:



4. A grey area in the middle of the screen is shown. Do “Click to Run Model”:



5. The model main screen will show up:

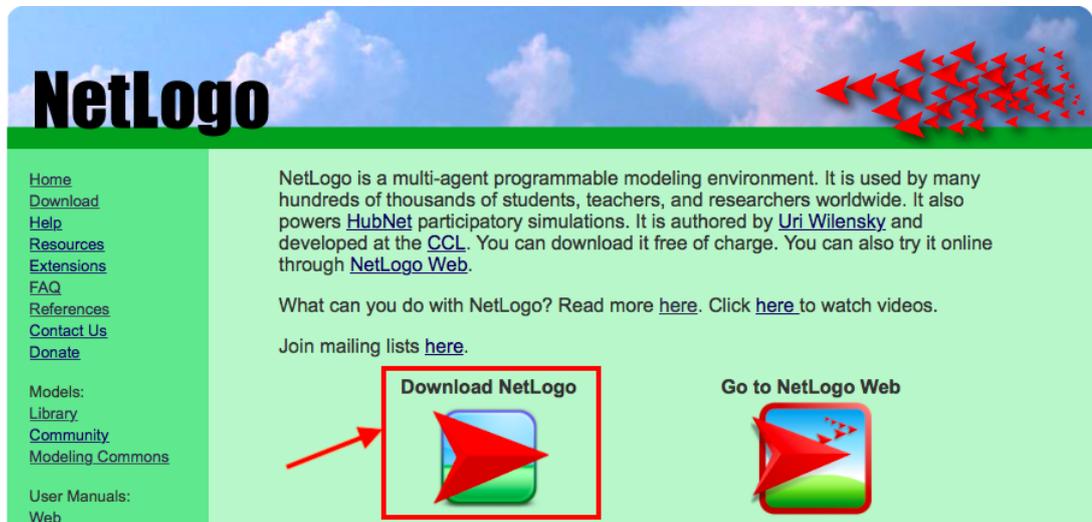


6. That’s all! Choose the running parameters in the control panel, click SETUP and then GO! Click the INFECT or OUTBREAK buttons at some point during the execution and you will see how the COVID-19 epidemics unfolds in the simulation view area, the monitors and the plots.

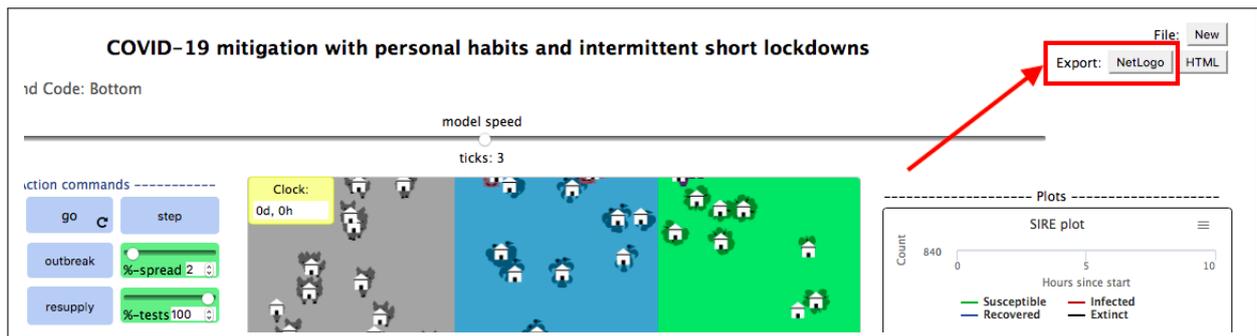
2.2 Desktop version

The desktop version is recommended if you want to try heavy experimentation, such as parameter tuning, average behaviour of multiple runs or simulations with large populations. For this purpose, COVID-19 Simulator runs over the NetLogo desktop simulation platform [2]. In this case, you need to go through the following steps:

1. Download and install the NetLogo desktop software. For this purpose, go to <http://ccl.northwestern.edu/netlogo/>, click in “Download NetLogo” and follow the instructions:

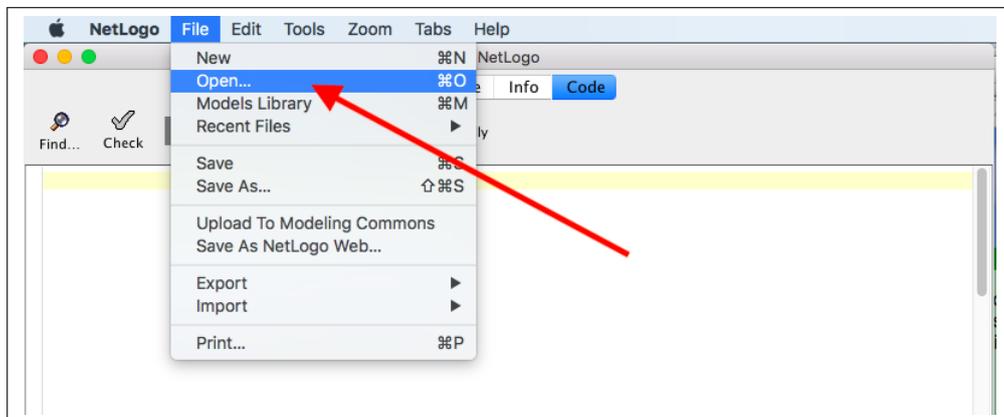


2. Download the COVID-19 Simulator model file from the model webpage, using the “Export” button:



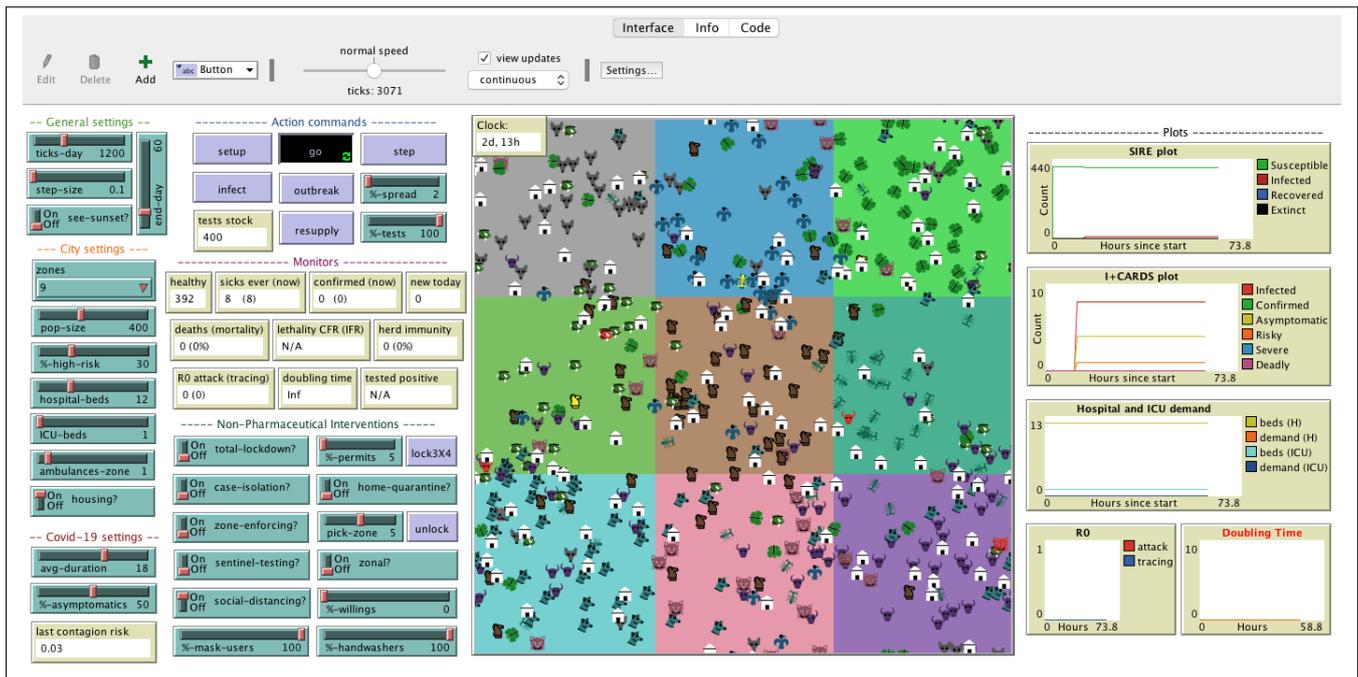
A file called *COVID-19 mitigation with personal habits and intermittent short lockdowns.nlogo* would be downloaded to your local disk.

3. Run NetLogo on your computer. Choose the menu option *File* → *Open*:



Locate the COVID-19 Simulator .nlogo file that you downloaded previously and open it.

4. The COVID-19 Simulator main screen will show up:



That's it! Choose the running parameters in the control panel, click SETUP and then GO! Click the INFECT or OUTBREAK buttons at some point during the execution and you will see how the COVID-19 epidemics unfolds in the simulation view area, the monitors and the plots.

2.3 References

- [2] Wilensky, U. (1999). NetLogo. <http://ccl.northwestern.edu/netlogo/>. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

Chapter 3

Source code

```
;; -----  
;; COVID-19 epidemic simulation with Non-Pharmaceutical Interventions,  
;; including a novel zonal restraint NPI.  
;;  
;; A model by Sergio Rojas-Galeano and Lindsay Alvarez  
;; v1.27 Copyright (c) September 2020 The authors  
;; Correspondance email: srojas@udistrital.edu.co  
;; Universidad Distrital Francisco Jose de Caldas, Bogota, Colombia  
;;  
;; This program is free software: you can redistribute it and/or modify  
;; it under the terms of the GNU General Public License (GPLv3)  
;; (see license at: https://www.gnu.org/licenses/gpl-3.0.txt)  
;;  
;; The model is made publicly available in the hope that it will be useful  
;; to modelers, but WITHOUT ANY WARRANTY whatsoever (see license for details).  
;; -----  
  
;; Define globals  
globals [  
  daytime? ; is it day or night? ( 1 day + 1 night = ticks-day)  
  sort-codes ; a list of codes to identify each zone of a city  
  shapes-list ; a list of shapes to identify agents of the same zone  
  colors-list ; a list of colors to identify different zones  
  day hour ; the current day and hour since simulation started  
  sick-days ; list of daily count of sick  
  n-cases ; number of overall COVID-19 sick people  
  n-confirmed ; number of confirmed COVID-19 sick people  
  n-tested ; number of overall people tested by sentinel  
  n-positives ; number of people that tested COVID-19 positive  
  doubling-time ; estimated days to double today's number of sick  
  R0 S0 R0_ ; reproduction number and initial Susceptibles  
  p-contagion ; probability of contagion on a single encounter  
  flex3X4? ; is it flexible lockdown on or off (i.e. "accordion strategy")?  
]  
  
;; Define breeds for healthy and infected people  
breed[ healthies healthy ]  
breed[ sick sick ]  
breed[ deaths death ]  
breed[ houses house ]  
breed[ ambulances ambulance ]  
  
;; Define attributes for patches  
patches-own [  
  zone ; the zone code of this patch  
]  
  
;; Define attributes of all the people  
turtles-own [  
  homebase ; the home patch of this person  
  scope ; the reach of distance away from home for this person  
  speed ; how fast does he/she move? A speed of 0 is still  
  unlocked? ; is the person free from lockdown?  
  tested? ; was the person tested by sentinel test?  
  contagions ; how many people this person infected if he/she ever got sick  
  mask-habit? ; is the person willing to wear protection mask?  
  wash-habit? ; is the person willing to wash his hands regularly?  
]  
  
;; Define attributes for sick people only  
sicks-own [  
  days-to-cure ; the actual duration of the illness for this person  
  recovery ; counter of days remaining to recovery  
  confirmed? ; is the person isolated at homebase?  
  asymptomatic? ; is the person asymptomatic?  
  risky? ; is the person high-risk due to existing factor (obese, diabetes, older, etc)  
  severe? ; is the person in severe condition?  
  deadly? ; is the person in deadly (critical) condition?  
  hospitalised? ; has he/she been admitted to hospital?
```

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    ICU-admitted?          ; has he/she been admitted to ICU?
  ]

;; Define attributes for healthy people only
healthies-own [
  immune?                ; has the person recovered and acquired immunity?
]

;; Define attributes for ambulances
ambulances-own [
  tests-stock            ; how many tests in stock
  tests-supply           ; numbers of tests to top-up (depends on amount of zone residents)
]

;; One iteration of simulation's steps
to go
  if ticks = ticks-day / 2 [ outbreak ] ; Epidemic begins with outbreak at 0d:12h (enable this line only for
    BehaviourSpace experiments)
  ifelse day < end-day [ tick ] [ stop ] ;screenshot stop ]
  lifestyle
  epidemic
  isolation
  quarantine
  distancing
  sentinel
  lockdown
  illness
  clock
  indicators
end

;; Simulate everyday routine of people
to lifestyle
  ask (turtle-set healthies sick with [not confirmed?] ) [
    if zone-enforcing? [
      if zone != [zone] of homebase [ face homebase fd 0.5 ] ; if away from resident zone, head back
    ]
    forward speed ; move ahead
    if distance homebase > scope [ face homebase ] ; if too far from home, head back
    set heading heading + (random-float 3 - random-float 3) ; change direction swiftly
  ]
end

;; Spread the infection from sick not yet isolated, to healthies
to epidemic
  ask sick with [not confirmed?] [
    let counter 0 ; number of contagions made by this sick
    let sick-masked? mask-habit? ; is the sick wearing mask?

    ask healthies with [not immune?] in-radius .5 [
      let healthy-masked? mask-habit? ; is the healthy wearing mask?

      ;; Set contagion risk depending on mask-wearing habits
      set p-contagion contagion-risk sick-masked? healthy-masked?

      ;; Contagion risk may decrease further depending on hand-washing habits of healthies
      if wash-habit? [ set p-contagion (p-contagion * 0.3) ] ; P(Contagion | p-contagion, healthy-washer?)

      if random-float 1 < p-contagion [
        get-sick
        set counter counter + 1
      ]
    ]
    set contagions contagions + counter
  ]
end

;; Probability of contagion depending on mask wearing combination
to-report contagion-risk [sick-masked? healthy-masked?]
  let p 0
  if not sick-masked? and not healthy-masked? [ set p 0.9 ] ; P(Contagion | False, False)
  if not sick-masked? and healthy-masked? [ set p 0.5 ] ; P(Contagion | False, True )
  if sick-masked? and not healthy-masked? [ set p 0.3 ] ; P(Contagion | True, False)
  if sick-masked? and healthy-masked? [ set p 0.1 ] ; P(Contagion | True, True)
  report p
end

;; Make a single person ill
to get-sick
  ;; S->I (set the initial properties of a sick person)
  set breed sick
  set shape item ([zone] of homebase) shapes-list
  set confirmed? false
  set tested? false
  set severe? false
  set deadly? false
  set hospitalised? false
  set ICU-admitted? false

  ;; Set stochastic attributes
  set days-to-cure abs int random-normal avg-duration 4 ; duration of illness for this sick
  set recovery 0 ; initial count of days until recovery
  set asymptomatic? (random 100) < %-asymptomatics ; is this an asymptomatic patient?

```

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set risky? (random 100) < %-high-risk and not asymptomatic? ; is it high-risk (co-morbidities) given not
asymptomatic?
set color ifelse-value asymptomatic? [ yellow ] [ red ]

;; Update how many cases so far
set n-cases n-cases + 1
end

;; Ask confirmed sick people to stay home
to isolation
;; If quarantine on, enforce isolation of symptomatic
ifelse case-isolation? [
  ask sick with [ not asymptomatic? and not confirmed? ] [
    move-to homebase
    set confirmed? true
    set n-confirmed n-confirmed + 1 ; these sick are now confirmed cases
  ]
]
;; Else lift isolation, except if was sent sentinel testing
[
  ask sick with [ not tested? and confirmed? ] [
    set confirmed? false
    set n-confirmed n-confirmed - 1 ; these sick are set back to not confirmed cases
  ]
]

;; Decorate houses with color of isolated people
ask houses [
  set color ifelse-value any? sick-here with [ not asymptomatic? ] [ red ]
  [ ifelse-value any? sick-here with [ asymptomatic? ] [ yellow ] [ white ] ]
]
end

;; Ask housemates of isolated people to stay home
to quarantine
if home-quarantine? [
  ask sick with [ confirmed? ] [
    let sick-home homebase
    ask other turtles with [ homebase = sick-home ] [ move-to homebase ]
  ]
]

;; Decorate houses with color of quarantined people
ask houses [
  set color ifelse-value any? sick-here with [ not asymptomatic? ] [ red ]
  [ ifelse-value any? sick-here with [ asymptomatic? ] [ yellow ] [ white ] ]
]
end

;; Avoid contacting nearby people (closer than than min-dist)
to distancing
if social-distancing?
[ let people (turtle-set healthies sick)
  let willings (count people * %-willing / 100)
  ask n-of willings people [
    if any? other people in-radius 0.6 [ ; a radius of 0.6 is slightly higher than the 0.5 threshold to
      contagion
      let closest min-one-of other people [distance myself]
      face closest rt 180 ; head in the opposite direction of closest person
    ]
  ]
]
end

;; Ask ambulances to catch sick by mass testing
to sentinel
ifelse sentinel-testing? [
  ask ambulances [
    st
    if tests-stock > 0 [
      ;; Move ambulances around
      forward speed
      if zonal? [ if zone != [zone] of homebase [ face homebase fd 0.5 ] ] ; keep ambulance in-zone
      set heading heading + (random-float 10 - random-float 10) ; change ambulance's heading
      randomly
    ]

    ;; Pick nearby and perform tests
    let target-people ((turtle-set healthies sick) in-radius 5) with [not tested?]
    ask target-people [
      if is-sick? self and not confirmed? [ ; if sick and not isolated,
        target is positive
        move-to homebase set confirmed? true
        set n-positives n-positives + 1 ; update count positives tests
        so far
        set n-confirmed n-confirmed + 1 ; update count of confirmed
        cases so far
      ]
      set tested? true ; mark this person as tested
    ]
    set n-tested n-tested + (count target-people) ; update count of tests made so
    far
    set tests-stock tests-stock - (count target-people) ; update stock of tests
    available
  ]
]
end

```

```

]
;; Else, stop and hide ambulances
[ ask ambulances [ ht ] ]
end

;; Enforce everyone staying home, except for a few permits
to lockdown
if (hour mod 24) = 0 [ ; lockdown starts or ends at 00:00 of
  next day
  ifelse total-lockdown? [
    let people (turtle-set healthies sick) with [not unlocked?] ; for people not in an unlocked zone
    ask people [ move-to homebase set speed 0 ] ; sent everyone home, not confirmed
    foreach sort-codes [
      z -> let residents people with [ zone = z ]
      let permits (count residents * %-permits / 100)
      ask n-of permits residents [ set speed step-size ]
    ]
    if flex3X4? and (day mod 7) >= 3 [ ; apply flexible lockdown: 3 days out of
      7 days period
      ask people [ set speed step-size ]
    ]
  ]
;; Else unlock everyone
[
  ask (turtle-set healthies sick) [ set speed step-size set unlocked? false ]
  if flex3X4? [ lock3X4 ]
]
]
end

;; Allow to lift total lockdown by unlocking zones gradually
to unlock
;let pick-zone random zones
ask (turtle-set healthies sick) with [ zone = (pick-zone - 1) ] [ set speed step-size set unlocked? true ]
;not unlocked? ]
end

;; Enable/disable 3x4 flexible lockdown i.e. "accordion rule": 3 days lockdown by 4 days free movement
to lock3X4
set flex3X4? (not flex3X4?) ; flip to the opposite value
ask patch (min-pxcor + 20) (min-pycor + 2) [ ; show/hide indicator label at bottom-left corner
  set plabel-color black
  set plabel ifelse-value flex3X4? [ "3x4_ON" ] [ "" ]
]
end

;; Simulate illness evolution in each person
to illness
if (ticks mod ticks-day) = 0 [ ; illness unfolds in a daily basis

  ;; I->R (sicks recovering after days-to cure)
  ask sick [
    set recovery recovery + 1 ; countdown of days left to recover
    if recovery >= days-to-cure [ get-well ] ; if recovery time over, the person is cured
  ]

  ;; I->E (sicks getting extinct, that is, dead)
  ask sick with [not asymptomatic?] [
    ;; Define probability of death
    let p 0.005 ; P(Extinct | Symptomatic)
    if deadly? and not ICU-admitted? [ set p 1.0 ] ; P(Extinct | Deadly, no ICU)
    if deadly? and ICU-admitted? [ set p 0.5 ] ; P(Extinct | Deadly, ICU)
    if severe? and not hospitalised? [ set p 0.2 ] ; P(Extinct | Severe, Hospitalised)
    if severe? and hospitalised? [ set p 0.05 ] ; P(Extinct | Severe, no Hospitalised)

    ;; Death may occur any day within days-to-cure, with triangular probability distribution peaking at
    half the days-to-cure
    let day-chance cdf-triangle recovery days-to-cure ; CDF of triangle distribution

    ;; Simulate death
    let r random-float 1.0
    if r < (p * day-chance) [ pass-away ]
  ]

  ;; I+Severe
  ask sick with [not asymptomatic? and not (severe? or deadly?)] [
    let p 0.0
    if not risky? [ set p 0.05 ] ; P(Severe | Symptomatic, no Risky)
    if risky? [ set p 0.25 ] ; P(Severe | Symptomatic, Risky)

    ;; Severity may arise any day within days-to-cure, following an uniform distribution
    let day-chance recovery / days-to-cure ; CDF of uniform distribution

    ;; Simulate severity
    let r random-float 1.0
    if r < (p * day-chance) [ set severe? true ]
  ]

  ;; I+Deadly
  ask sick with [severe?] [
    let p 0.0
    if not risky? [ set p 0.05 ] ; P(Deadly | Severe, no Risky)
    if risky? [ set p 0.25 ] ; P(Deadly | Severe, Risky)

    ;; Deadliness may arise any day within days-to-cure, following an uniform distribution

```

```

let day-chance recovery / days-to-cure          ; CDF of uniform distribution

;; Simulate deadliness
let r random-float 1.0
if r < (p * day-chance) [ set deadly? true set severe? false ]
]

;; I+Hospitalised
let occupied count sick with [severe? and hospitalised?]
let required count sick with [severe? and not hospitalised?]
let incoming min list (hospital-beds - occupied) required           ; how many can be
hospitalised?
ask n-of incoming sick with [severe? and not hospitalised?] [      ; hospitalised as many as
possible
set hospitalised? true
set tested? true           ; so they can't move even
when isolation off
if not confirmed? [ set confirmed? true set n-confirmed n-confirmed + 1 ] ; if wasn't confirmed yet,
confirm and update count
]

;; I+ICU-admitted
let occupied count sick with [deadly? and ICU-admitted?]
let required count sick with [deadly? and not ICU-admitted?]
let incoming min list (ICU-beds - occupied) required           ; how many can be admitted to
ICU?
ask n-of incoming sick with [deadly? and not ICU-admitted?] [    ; ICU-admit as many as
possible
set ICU-admitted? true
set tested? true           ; so they can't move even
when isolation off
if not confirmed? [ set confirmed? true set n-confirmed n-confirmed + 1 ] ; if wasn't confirmed yet,
confirm and update count
]
]
end

;; Compute Cumulative Distribution Function (CDF) of triangular distribution at a given number of days
elapsed (x) within illness period (width)
to-report cdf-triangle [x width]
;; Height of the inner triangle to obtain CDF, i.e. the value of the PDF on x
let height 2 * (width - abs (width - (2 * x))) / (width ^ 2)

;; If x is before peak, CDF is the area of the inner triangle with base x
ifelse x <= (width / 2) [
let base x
report height * base / 2
]
;; Else if x is after peak, CDF is to total area (1) minus area of inner triangle with base (width - x)
[
let base (width - x)
report 1 - (height * base / 2)
]
end

;; Become healthy again
to get-well
let old-shape shape
set breed healthies
set immune? true
set shape old-shape
set color white
set speed step-size
end

;; Become dead
to pass-away
if not confirmed? [ set confirmed? true set n-confirmed n-confirmed + 1 ] ; some cases are confirmed only
at death
set breed deaths
set shape "x"
set speed 0
set color black
end

;; Update counters of days and hours
to clock
set day int (ticks / ticks-day)          ; track of number of days elapsed since beginning
set hour int ((ticks / ticks-day) * 24)  ; track of number of hours elapsed since beginning
sunset
end

;; Record epidemic indicators
to indicators
;; Daily statistics are sick per day and doubling-time
if ticks mod ticks-day = 0 [
set sick-day lput (count sick) sick-day

;; Compute doubling time
;; see (Bakir, 2016, "Compound Interest Doubling Time Rule: Extensions and Examples from Antiquities.")
if any? sick[
ifelse (last sick-day) > (item (day - 1) sick-day)
[ set doubling-time ln 2 / ln ((last sick-day) / (item (day - 1) sick-day + 1E-10)) ]
[ set doubling-time "Inf" ]
]
]
end

```

```

]
if ticks mod (ticks-day / 24) = 0 [
  ;; Estimate R0 based on the final size of susceptibles in population
  ;; see (Dietz, 1993, "The estimation of the basic reproduction number for infectious diseases.")
  if S0 != 0 [
    let Sn count healthies with [ not immune? ] / pop-size
    set R0 (ln (S0 + 1E-10) - ln (Sn + 1E-10)) / (S0 - Sn + 1E-10)
  ]
  ;; Estimate R0_ with an individual-based approach, as the average of contagions per sick
  if any? turtles with [contagions > 0] [
    set R0_mean [contagions] of turtles with [contagions > 0]
  ]
]
end

;; Inoculate infection on one agent
to infect
  if any? healthies with [not immune?][
    ask one-of healthies with [not immune?] [ get-sick ]
  ]
]

;; Record the initial count of susceptibles for R0 computation
set S0 (count healthies with [not immune?]) / pop-size
end

;; Contagion by an outbreak
to outbreak
  ;; Infect a percentage of population
  repeat pop-size * (%-spread / 100) [ infect ]

  ;; Record the initial count of susceptibles for R0 computation
  set S0 (count healthies with [not immune?]) / pop-size
end

;; Light up or down the city depending on daytime
to sunset
  if see-sunset? [
    if (ticks mod (ticks-day / 2)) = 0 [
      ifelse daytime?
        [ ask patches [ set pcolor pcolor + 4 ] ]
        [ ask patches [ set pcolor pcolor - 4 ] ]
      set daytime? not daytime?
    ]
  ]
end

;; Get ready to go
to setup
  clear-all
  reset-ticks
  setup-globals
  setup-city
  setup-people
  setup-ambulances
  set daytime? false
  set flex3X4? false
end

;; Initialize global variables
to setup-globals
  ;; Codes to identify zones
  set sort-codes n-values zones [ i -> i ]

  ;; Residents of each zone are identified with different shapes and color
  set shapes-list [ "dog" "cat" "cow_skull" "fish_2" "chess_knight" "ant_2" "wolf_7" "bird"
    "butterfly_2" "rabbit" "bug" "spider" "ghost" "monster" "person" "fish" "sheep" "bee_2" ]
  set colors-list [ cyan pink violet green brown turquoise gray sky lime violet blue
    brown gray sky pink turquoise ]

  ;; Initialise daily sick, positives, total-tested, total and confirmed cases
  set sick-day [0]
  set n-positives 0 set n-tested 0 set n-cases 0 set n-confirmed 0

  ;; Initial value for doubling time
  set doubling-time 0.0
end

;; Split the city into zones and setup facilities
to setup-city
  set-patch-size 1.9

  ;; Layout a grid of patch square zones by assigning auxiliary codes
  let step world-width / sqrt zones
  ask patches [
    let units int ((pxcor + max-pxcor) / step)
    let tens int ((pycor + max-pycor) / step)
    set zone 10 * tens + units
  ]

  ;; Now map those auxiliary codes to consecutive sort-codes and corresponding colors
  let aux-codes sort remove-duplicates [zone] of patches
  (foreach aux-codes sort-codes [ [old new] -> ask patches with [zone = old] [set zone new] ])
  ask patches [ set pcolor (item zone colors-list) + 1 ]

```

```

;foreach sort-codes [ c -> ask one-of patches with [zone = c] [set plabel zone] ] ; display zone code on
view area

;; If housing, create houses
if housing? [
  create-houses pop-size / 4 [
    setxy random-xcor random-ycor
    set color white set shape "house" set size 9
  ]
]
end

;; Create initial population
to setup-people
  create-healthy pop-size [
    ;; Assign as homebase either a house if any, otherwise his initial position
    ifelse housing?
    [ set homebase one-of houses
      move-to homebase
    ] [ setxy random-xcor random-ycor
      set homebase patch-here
    ]
  ]

  ;; Assign color and shape depending on homebase's zone
  set color item zone colors-list - 2
  set shape item zone shapes-list
  set size 9
  set heading random 360
  set scope one-of (list 25 50 100 200) ; choose radomly movement range
  set immune? false
  set unlocked? false
  set tested? false
  set contagions 0
  set mask-habit? random 100 < %-mask-users ; set face mask protection social habit
  set wash-habit? random 100 < %-handwashers ; set hand-washing social habit
  set speed step-size ;0.1 ;0.5
  forward 3 ; peek out of house to be seen at the beginning
]
end

;; Create ambulances
to setup-ambulances
  foreach range zones [ z ->
    create-ambulances ambulances-zone [
      move-to one-of patches with [ zone = z ]
      set homebase patch-here
      set shape "ambulance_2" set size 12 set color white
      set speed 4 * step-size ; ambulances move faster than people
      let residents (turtle-set healthies sick) with [ zone = z ]

      ;; The amount of tests supply depends on residents population
      set tests-supply round (count residents * (%-tests / 100) / ambulances-zone )
      set tests-stock tests-supply ; initialise stock of tests
    ]
  ]
end

;; Replenish the stock of available tests in ambulances
to supply-ambulances
  ask ambulances [ set tests-stock tests-stock + tests-supply ]
end

;; Replenish an infinite stock of tests in ambulances
to supply-infinity
  ask ambulances [ set tests-stock 1000000 ]
end

;; Save a screenshot of the interface (view+plots, etc) in a file
to screenshot
  display
  ;export-interface (word "COVID19-NPI-ABM-" random 1000 random 1000 ".png")
end

```


Chapter 4

Software license

COVID-19 Simulator version 1.27

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