CSYS 300 – COMPLEX SYSTEMS FUNDAMENTALS, METHODS & APPLICATIONS

Agent-based Modeling Applications

Stephen J. Verzi
Sandia National Laboratories, New Mexico (USA)
Outline of Presentation

- Brief Biographical Note
- Where this Section Fits in the Structure of the Complex Systems Course
- Agent-based Modeling – Brief Introduction
- Modeling Population Health with Agents
- Example of Analysis Using Agent-based Population Model
- NetLogo Example
- Summary
- Question & Answer Session
CSYS 300 – COMPLEX SYSTEMS FUNDAMENTALS, METHODS & APPLICATIONS
Agent-based Modeling Applications

Brief Biographical Note on [Stephen J. Verzi]

- University of New Mexico, BS, MS, PhD, Artificial Intelligence & Analysis and Extension of Adaptive Resonance Theory Neural Networks
  - Design & code modeling & simulation framework for atmospheric light propagation
- SNL Work Experience [2004-present]
  - Neural models for cognitive processes (analogy, association, learning behavior)
  - Agent-based modeling of population health
- Professional organizations, etc relevant to Complex Systems
  - Tobacco Policy Modeling
  - American Academy of Health Behavior
  - Neural Networks Journal
CSYS 300 – COMPLEX SYSTEMS FUNDAMENTALS, METHODS & APPLICATIONS

Structure of the Course

- Fundamentals of Complex Systems
- Methods
  - Modeling Techniques
  - Approaches to Examining Complex Systems
- Applications
  - Examples of the use of complex systems fundamentals to solve problems
  - Learning how to use complex systems modeling tools

*Note: These approaches represent a simplified set of complex systems concepts chosen for the CSYS 300 systems lectures. Please see the initial two lectures for additional detail and expanded references.
Agent-based Modeling Applications

- Agent-based Modeling – Brief Introduction
History

- Von Neumann machine
- Cellular automata
- Game of life
- Game theory
  - Prisoner’s dilemma
- Biological models
  - Flocking
  - Artificial life
Features

- Autonomous
- Bounded rationality (agent operation)
- Heterogeneity
- Micro versus macro (or level of granularity of representation versus level of emergent phenomena)
- Computationally intensive
Composition

- Agents
  - Behavior
  - Learning/Adaptivity
- Interaction (network)
- World/Environment (non-agent)
Motivation

- Simple
  - Representation
  - Explanation
- Emergent phenomena
  - Explore macro through changes to micro
- Relationship to underlying data for parameterizing the model
  - Use human survey data
ABM Frameworks

- Sandia
  - N-Able
  - Snapdragon
  - Exchange
  - Loki
  - Population Structure Models

- Other
  - Repast
  - NetLogo
  - AnyLogic
  - Swarm
CSYS 300 – COMPLEX SYSTEMS FUNDAMENTALS, METHODS & APPLICATIONS
Agent-based Modeling Applications

- Modeling Population Health With Agents
Keys to Population Modeling

- Initial Population Distribution
  - Gender, Age
  - State
- Change in Population
  - Birth
  - Net Migration
  - Change in State (agent behavior)
- Aggregation of Subpopulations
  - Gender, Age
  - State
Agent Representation

- Each agent is composed of
  - Intrinsic qualities
    - ID
    - Gender
    - Race/Ethnicity
  - States
    - Age
    - Health
    - Product Use Status
  - Changes in state
    - Behaviors (agent choice)
    - Behavioral Consequences
    - Other
Changes in State

- Behavior
  - Start using product
  - Quit using product

- Behavioral Consequences
  - Health impact (change in disease state)
  - Death

- Other
  - Product use encouraged (industry marketing)
  - Product use discouraged (healthcare professional)
Agent-Based Model – Simulation

- Initialize agent population according to desired starting point
- Fixed-increment time advancement
  - Increment step = 1 year
- During each increment, each agent’s states are updated
  - Using the current time
    - Age increases once per year
  - Using each agent’s Markov Chain
    - Health is determined by probability of dying (by age, by gender, by smoking status) per year
    - Smoking status is determined by probability of initiating/ quitting (by age, by gender, by smoking status) per year
Agent-Based Model – Simulation

- Example of an agent in simulation

<table>
<thead>
<tr>
<th>Time</th>
<th>Agent ID</th>
<th>Gender</th>
<th>Age</th>
<th>Health</th>
<th>Cigarette Smoking Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>“Agent 01”</td>
<td>female</td>
<td>16</td>
<td>100</td>
<td>never-smoker</td>
</tr>
<tr>
<td>2</td>
<td>“Agent 01”</td>
<td>female</td>
<td>18</td>
<td>100</td>
<td>current-smoker</td>
</tr>
<tr>
<td>34</td>
<td>“Agent 01”</td>
<td>female</td>
<td>50</td>
<td>100</td>
<td>former-smoker</td>
</tr>
<tr>
<td>63</td>
<td>“Agent 01”</td>
<td>female</td>
<td>79</td>
<td>0</td>
<td>dead</td>
</tr>
</tbody>
</table>
Agent-Based Model – Simulation

- Cigarette smoking Markov chain

\[ \Pr_{\text{Never}} \{ \text{Initiate} \mid \text{Age} = 18, \text{Gender} = \text{female} \} = 0.045 \]

The probability of initiation for an 18 year-old female comes from analysis of NHIS data.
Agent-Based Model – Simulation

- Cigarette smoking Markov chain

Agent
- ID: “Agent 01”
- Gender: female
- Age: 50
- Health: 100 (alive)
- Cigarette Smoking Status: former-smoker

\[
\Pr_{\text{Smoker}} \{\text{Quit} \mid \text{Age} = 50, \text{Gender} = \text{female}\} = 0.034
\]

The probability of initiation for an 18 year-old female comes from analysis of NHIS data.
Agent-Based Model – Simulation

- Mortality Markov chain

\[
\Pr_{\text{Former}} \{ \text{Death} \mid \text{Age} = 79, \text{Gender} = \text{female}, \text{QuitAge} = 50 \} = 0.029
\]

The probability of dying for an 79 year-old female former smoker who quit at age 50 comes from NHIS-LMF and Thun \((0.027005807 \times 1.09 = 0.0294932963)\)

- **Agent**
  - ID: “Agent 01”
  - Gender: female
  - Age: 79
  - Health: 0 (dead)
  - Cigarette Smoking Status: former-smoker

\[ \text{time} = 63 \]
Example of Analysis Using Agent-based Population Model
Parameters

- Baseline Model
  - Initial population
    - Population – U.S. Census 2000
    - Smoking Prevalence – Anderson et al., 2011
      - Current-smoker
      - Former-smoker
  - Birth Rate – U.S. Census 2008 Population Projection
  - Immigration Rate – U.S. Census 2008 Population Projection
# Initial Population

- **U.S. Census**

## Table 7. Resident Population by Sex: Age to 2009

<table>
<thead>
<tr>
<th>Age</th>
<th>1980 Total Male</th>
<th>1980 Total Female</th>
<th>2000 Total Male</th>
<th>2000 Total Female</th>
<th>2009 Total Male</th>
<th>2009 Total Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Under 5 years</td>
<td>220,546</td>
<td>110,053</td>
<td>110,493</td>
<td>248,701</td>
<td>121,284</td>
<td>127,417</td>
</tr>
<tr>
<td>5 to 9 years</td>
<td>16,700</td>
<td>8,539</td>
<td>8,161</td>
<td>20,042</td>
<td>9,256</td>
<td>9,786</td>
</tr>
<tr>
<td>10 to 14 years</td>
<td>18,242</td>
<td>9,319</td>
<td>8,923</td>
<td>20,528</td>
<td>10,250</td>
<td>10,278</td>
</tr>
<tr>
<td>15 to 19 years</td>
<td>21,168</td>
<td>10,755</td>
<td>10,413</td>
<td>20,193</td>
<td>10,361</td>
<td>10,832</td>
</tr>
<tr>
<td>20 to 24 years</td>
<td>21,319</td>
<td>10,663</td>
<td>10,656</td>
<td>20,585</td>
<td>10,699</td>
<td>10,886</td>
</tr>
<tr>
<td>25 to 29 years</td>
<td>19,521</td>
<td>9,705</td>
<td>9,816</td>
<td>20,336</td>
<td>10,708</td>
<td>10,628</td>
</tr>
<tr>
<td>30 to 34 years</td>
<td>17,561</td>
<td>8,677</td>
<td>8,884</td>
<td>20,051</td>
<td>10,322</td>
<td>10,189</td>
</tr>
<tr>
<td>35 to 39 years</td>
<td>13,965</td>
<td>6,662</td>
<td>7,304</td>
<td>22,707</td>
<td>11,319</td>
<td>11,388</td>
</tr>
<tr>
<td>40 to 44 years</td>
<td>11,668</td>
<td>5,706</td>
<td>5,962</td>
<td>22,442</td>
<td>11,130</td>
<td>11,313</td>
</tr>
<tr>
<td>45 to 49 years</td>
<td>11,090</td>
<td>5,399</td>
<td>5,691</td>
<td>22,174</td>
<td>10,924</td>
<td>11,250</td>
</tr>
<tr>
<td>50 to 54 years</td>
<td>11,710</td>
<td>5,621</td>
<td>6,089</td>
<td>22,286</td>
<td>11,204</td>
<td>11,082</td>
</tr>
<tr>
<td>55 to 59 years</td>
<td>11,615</td>
<td>5,482</td>
<td>6,133</td>
<td>22,140</td>
<td>11,059</td>
<td>11,081</td>
</tr>
<tr>
<td>60 to 64 years</td>
<td>10,088</td>
<td>4,970</td>
<td>5,118</td>
<td>22,061</td>
<td>10,924</td>
<td>11,137</td>
</tr>
<tr>
<td>65 to 74 years</td>
<td>15,841</td>
<td>7,677</td>
<td>8,164</td>
<td>24,048</td>
<td>12,101</td>
<td>11,947</td>
</tr>
<tr>
<td>75 to 84 years</td>
<td>7,729</td>
<td>2,867</td>
<td>4,862</td>
<td>20,146</td>
<td>10,128</td>
<td>10,018</td>
</tr>
<tr>
<td>85 years and over</td>
<td>2,460</td>
<td>1,052</td>
<td>1,408</td>
<td>4,340</td>
<td>1,817</td>
<td>2,523</td>
</tr>
</tbody>
</table>

1. Total population count has been revised since the 1980 Census publications. Numbers by age and sex have not been corrected.  
2. The data shown have been modified from the official 1990 Census counts. See text of this section for explanation.  
3. The April 1, 2000 population estimates (248,790,925) includes count question resolution corrections processed through August 1997. It generally does not include adjustments for census coverage errors. However, it includes adjustments estimated for the 1995 Test Census in various locations in California, New Jersey, and Louisiana; and the 1998 census dress rehearsals in locations in California and Wisconsin. These adjustments amounted to a total of 81,022 persons.  
4. The April 1, 2000 population estimates base reflects changes to the Census 2000 population from the Count Question Resolution program.


2000 U.S. Census

Fraction of Population

0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8

Age


female
male
Initial Population (2000 Census & NHIS)

Fraction of Population

Age

Female

Male

Smoking Status:
- never
- current
- former
- former-smoker male
- former-smoker female
- current-smoker male
- current-smoker female

Fraction of Population

0.010 0.008 0.006 0.004 0.002 0.000 0.002 0.004 0.006 0.008 0.010

0

5

10

15

20

25

30

35

40

45

50

55

60

65

70

75

80

85

90

95

100+
Modeling Tobacco Use

- Single product
  - Cigarettes
  - Smokeless
- Product pairs
- Multiple products
  - # states, transitions – exponential in # products
Single Product

- 18 year-old male (cigarettes)
Single Product

- 48 year-old male (cigarettes)
Markov Model

- Single Product Probabilities
  - Initiation
  - Cessation
  - Mortality
    - Computed using never smoker death rates modified by relative risk factors, by age and gender

\[
\begin{align*}
\Pr_S \{D \mid A, G\} &= RR_S (A, G) \cdot \Pr_N \{D \mid A, G\} \\
\Pr_F \{D \mid A, G\} &= RR_F (A, QA, G) \cdot \Pr_N \{D \mid A, G\} \\
\Pr_N \{D \mid A, G\} &= \text{Never-smoker Mortality (Age } A, \text{ Gender } G) \times \text{Lee-Carter mortality scale factor}
\end{align*}
\]

\(S = \text{current smoker}, \ F = \text{former smoker} \text{ and } N = \text{never smoker}. \)
\(D = \text{death}, \ A = \text{age}, \ G = \text{gender}, \ QA = \text{quit age} \text{ and } RR = \text{relative risk.}\)
Parameters

- **Baseline Model**
  - Smoking Initiation/Cessation – Anderson et al., 2011
    - Female
    - Male
  - Mortality Rate
    - Never-smoker
      - < 35 – U.S. Census 2000
      - ≥ 35 – NHIS-LMF (Apelberg & Rostron), 2011
  - Relative Risk – Thun, 2010
    - Current-smoker
    - Former-smoker
Cigarette Smoking Initiation

- Anderson et al., 2011

Cigarette smoking initiation rates are taken from NHIS data, analyzed by Anderson et al., converted into probabilities for each age.
Cigarette smoking cessation rates are taken from NHIS data, analyzed by Anderson et al., converted into probabilities for each age.
Never Smoker Mortalities

- U.S. Census and NHISLMF (Apelberg & Rostron 2012)

Never smoker mortality rates are taken from U.S. Census 2000 data for ages under 35 and from NHISLMF for ages 35 and above.
Mortality scale factors are taken from Lee-Carter and model decline in mortality probability due to improvements in medicine and health care.
Current- and former-smoker relative risk factors are provided by CTP (Brian Rostron and Ben Apelberg) and are derived from Thun’s analysis of the CPS-II survey data for each age.
Model Verification

- Population Projection

Close match with Census projections.
Model Validation

- Smoking Prevalence

Adult prevalence comparison of Sandia Baseline (green triangles) versus CDC crude values (red squares) and Mendez & Warner (blue X’s) and SimSmoke (blue +’s) projections.
Analysis Results

- Yearly Tobacco-Attributable Mortalities

CDC reports 440,000 (393,000 without second-hand smoke and in-home fires) deaths annually due to smoking for years 2000-2004 (CDC 2008).

Sandia Baseline computes 401,000 smoking-attributable deaths where 95% CI is (389,000 – 413,000) for 2000-2004.
### Results Comparison

#### Comparison of Estimated Tobacco-Attributable Mortalities

<table>
<thead>
<tr>
<th></th>
<th>Females</th>
<th></th>
<th>Males</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fenelon, Preston (2011)</td>
<td>0.17</td>
<td>0.17</td>
<td>0.22</td>
<td>0.21</td>
</tr>
<tr>
<td>Preston, Glei Wilmoth (2010)</td>
<td>0.19</td>
<td>0.2</td>
<td>0.23</td>
<td>0.22</td>
</tr>
<tr>
<td>Rostron (2010)</td>
<td>0.14</td>
<td></td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>Peto-Lopez</td>
<td>0.21</td>
<td></td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>CDC Method</td>
<td></td>
<td>0.15</td>
<td></td>
<td>0.23</td>
</tr>
<tr>
<td>Rogers</td>
<td>0.13</td>
<td></td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>Sandia Baseline</td>
<td>0.12</td>
<td>0.11</td>
<td>0.25</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Other results based on regression-fit modeling.
Analysis Capability

- Sandia model can project attributable mortality fraction

![Attributable Mortality Chart](image)
Sensitivity Analysis and Uncertainty Quantification

- More stochastic runs are better
CSYS 300 – COMPLEX SYSTEMS FUNDAMENTALS, METHODS & APPLICATIONS
Agent-based Modeling Applications

- NetLogo Example
Population Simulation with NetLogo

- Download and install NetLogo (agree to license conditions/term)
  - http://ccl.northwestern.edu/netlogo/
- Launch NetLogo
- Start a new model
Population Simulation with NetLogo

- Add “setup” and “go” buttons

- Add “initial-population-count” and “last-year” input boxes

“go” button disabled until simulation starts
Population Simulation with NetLogo

- Add initial population group fractions (3 groups: nevers, currents and formers)
  - initial_never_fraction: 54.4%
  - initial_current_fraction: 23.3%
  - initial_former_fraction: 22.3%
  - These should sum to 100%

- Add birth and immigration rates
  - birth_rate: 14.4 births / 1000 people / year
  - immigration_rate: 4.22 people / 1000 people / year
Population Simulation with NetLogo

- Add immigration group fractions (same 3 groups)

![Image of immigration group fractions](immigrant-never-fraction: 40%)

- Add transitions (never -> current and current-> former)

![Image of transition probabilities](initiation-probability: 0.00695)

These should sum to 100%
Population Simulation with NetLogo

- Add mortalities and relative risks

\[
\Pr_S \{D\} = RR_S \cdot \Pr_N \{D\} \\
\Pr_F \{D\} = RR_F \cdot \Pr_N \{D\} \\
\Pr_N \{D\} = \text{never-mortality-probability}
\]

\(S = \text{current smoker}, \ F = \text{former smoker} \text{ and } N = \text{never smoker.} \)
\(D = \text{death} \text{ and } RR = \text{relative risk.} \)
Population Simulation with NetLogo

- Add output plots
Population Simulation with NetLogo

- Run model simulation
Population Simulation with NetLogo

- Code

```plaintext
breed [nevers never]
breed [currents current]
breed [formers former]
turtles-own [health] ;; all population entities have health

to setup
clear-all
set-default-shape nevers "face happy"
create-nevers 10000 * initial-never-fraction / (initial-never-fraction + initial-current-fraction + initial-former-fraction) ;; create the nevers
[
  set color green
  set size 1.5 ;; easier to see
  set health 100
  setxy random-xcor random-ycor
]
set-default-shape currents "face sad"
create-currents 10000 * initial-current-fraction / (initial-never-fraction + initial-current-fraction + initial-former-fraction) ;; create the currents
[
  set color red
  set size 1.5 ;; easier to see
  set health 100
  setxy random-xcor random-ycor
]
set-default-shape formers "face neutral"
create-formers 10000 * initial-former-fraction / (initial-never-fraction + initial-current-fraction + initial-former-fraction) ;; create the formers
[
  set color blue
  set size 1.5 ;; easier to see
  set health 100
  setxy random-xcor random-ycor
]
set new-currents 0
set new-formers 0
reset-ticks
end
```
Population Simulation with NetLogo

- Another simulation
Summary

- Use agent-based modeling
  - Easy to setup and simple to explain
  - Model aggregate phenomena with elemental building blocks
  - Direct relationship to available data
Population Modeling Team

- Nancy Brodsky
- Theresa Brown
- Eric Vugrin
- Louise Maffitt
- David Miller
- Will Peplinski
- Steve Verzi
- Leland Evans
- Pat Finley
- Tom Moore

- Jacob Hobbs
- Joe Collard
- Greg Lambert
- Braeton Smith
- Nick Childress
- Sarah Parro
CSYS 300 – COMPLEX SYSTEMS FUNDAMENTALS, METHODS & APPLICATIONS
Agent-based Modeling Applications

QUESTIONS & ANSWERS

Stephen J. Verzi
06132
Sandia National Laboratories
Albuquerque NM 87185-1138
sjverzi@sandia.gov
Complete Code for Example NetLogo Population Model
Population Simulation with NetLogo

- Code

```plaintext
breed [nevers never]
breed [currents current]
breed [formers former]
turtles-own [health] ;; all population entities have health

to setup
  clear-all
  set-default-shape nevers "face happy"
  create-nevers 1000 * initial-never-fraction / (initial-never-fraction + initial-current-fraction + initial-former-fraction) ;; create the nevers
  [  
    set color green
    set size 1.5 ;; easier to see
    set health 100
    setxy random-xcor random-ycor
  ]
  set-default-shape currents "face sad"
  create-currents 1000 * initial-current-fraction / (initial-never-fraction + initial-current-fraction + initial-former-fraction) ;; create the currents
  [  
    set color red
    set size 1.5 ;; easier to see
    set health 100
    setxy random-xcor random-ycor
  ]
  set-default-shape formers "face neutral"
  create-formers 1000 * initial-former-fraction / (initial-never-fraction + initial-current-fraction + initial-former-fraction) ;; create the formers
  [  
    set color blue
    set size 1.5 ;; easier to see
    set health 100
    setxy random-xcor random-ycor
  ]
  set new-currents 0
  set new-formers 0
  reset-ticks
end
```
Population Simulation with NetLogo

- Code (cont.)

```plaintext
<table>
<thead>
<tr>
<th>to go</th>
</tr>
</thead>
<tbody>
<tr>
<td>if not any? turtles [] stop []</td>
</tr>
<tr>
<td>if ticks &gt; last-year [ stop ]</td>
</tr>
<tr>
<td>ask nevers [] move</td>
</tr>
<tr>
<td>initiate []</td>
</tr>
<tr>
<td>ask currents [] move</td>
</tr>
<tr>
<td>quit</td>
</tr>
<tr>
<td>ask formers [] move</td>
</tr>
<tr>
<td>transition</td>
</tr>
<tr>
<td>immigration</td>
</tr>
<tr>
<td>birth</td>
</tr>
<tr>
<td>ask nevers [] never-death</td>
</tr>
<tr>
<td>ask currents [] current-death</td>
</tr>
<tr>
<td>ask formers [] former-death</td>
</tr>
<tr>
<td>tick</td>
</tr>
<tr>
<td>end</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>to move [] turtle procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>rt random 50</td>
</tr>
<tr>
<td>lt random 50</td>
</tr>
<tr>
<td>fd 1</td>
</tr>
<tr>
<td>end</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>to initiate [] nevers procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>if random-float 1 &lt; initiation-probability [] throw &quot;dice&quot; to see if you will initiate</td>
</tr>
<tr>
<td>set health 0</td>
</tr>
<tr>
<td>set new-currents (new-currents + 1)</td>
</tr>
<tr>
<td>end</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>to quit [] currents procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>if random-float 1 &lt; cessation-probability [] throw &quot;dice&quot; to see if you will quit</td>
</tr>
<tr>
<td>set health 0</td>
</tr>
<tr>
<td>set new-formers (new-formers + 1)</td>
</tr>
<tr>
<td>end</td>
</tr>
</tbody>
</table>
```
Population Simulation with NetLogo

- Code (cont.)

```plaintext
to transition ;; turtle procedure
  if new-currents > 0 [  
    create-currents new-currents
    [  
      set color red
      set size 1.5 ;; easier to see
      set health 100
      setxy random-xcor random-ycor
    ]
    set new-currents 0
  ]
  if new-formers > 0 [  
    create-formers new-formers
    [  
      set color blue
      set size 1.5 ;; easier to see
      set health 100
      setxy random-xcor random-ycor
    ]
    set new-formers 0
  ]
end
```
Population Simulation with NetLogo

- Code (cont.)

```netlogo
; Code (cont.)

to immigration
  set population-count 0 ; count turtles
  if immigrant-nevers > 0 [create-nevers immigrant-nevers
    ; set color green
    ; set size 1.5 ; easier to see
    ; set health 100
    ; setxy random-xcor random-ycor
  ]
  if immigrant-currents > 0 [create-currents immigrant-currents
    ; set color red
    ; set size 1.5 ; easier to see
    ; set health 100
    ; setxy random-xcor random-ycor
  ]
  if immigrant-formers > 0 [create-formers immigrant-formers
    ; set color blue
    ; set size 1.5 ; easier to see
    ; set health 100
    ; setxy random-xcor random-ycor
  ]
end

to birth
  set population-count count turtles
  set birth-nevers (birth-rate / 1000 * population-count)
  if birth-nevers > 0 [create-nevers birth-nevers
    ; set color green
    ; set size 1.5 ; easier to see
    ; set health 100
    ; setxy random-xcor random-ycor
  ]
end
```
Population Simulation with NetLogo

- Code (cont.)

```plaintext
to never-death ;; nevers procedure
  if random-float 1 < never-mortality-probability [ die ]
end

to current-death ;; currents procedure
  if random-float 1 < never-mortality-probability * current-relative-risk [ die ]
end

to former-death ;; formers procedure
  if random-float 1 < never-mortality-probability * former-relative-risk [ die ]
end
```