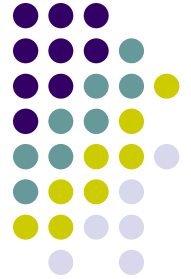


Modelling Agent-Based Systems Using System Dynamics

Jim Duggan,

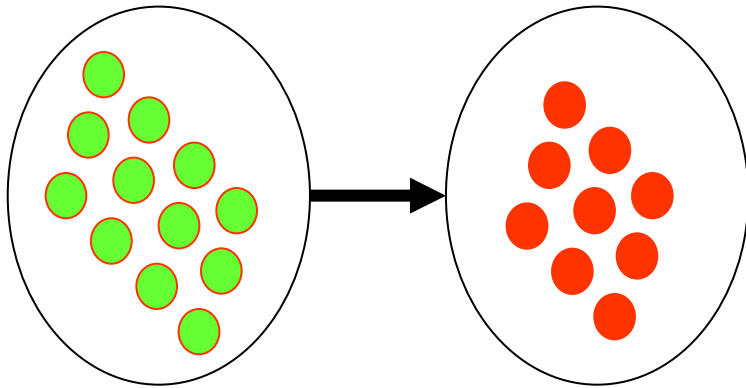
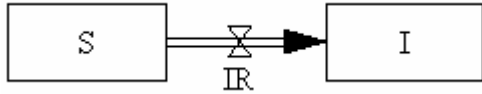
Department of Information Technology,
Faculty of Engineering,
National University of Ireland, Galway.



Workshop Overview

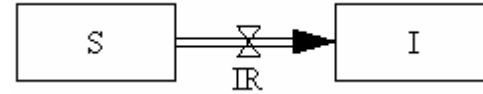
- Summary of Approach
- Case Study (SIR)
- Model Building
 - Aggregate Model
 - Agent Models
 - Runtime Model
- Running the Model
- Display Results via Excel

Aggregate

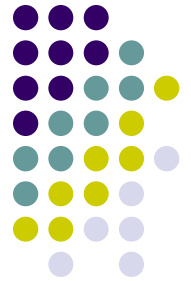
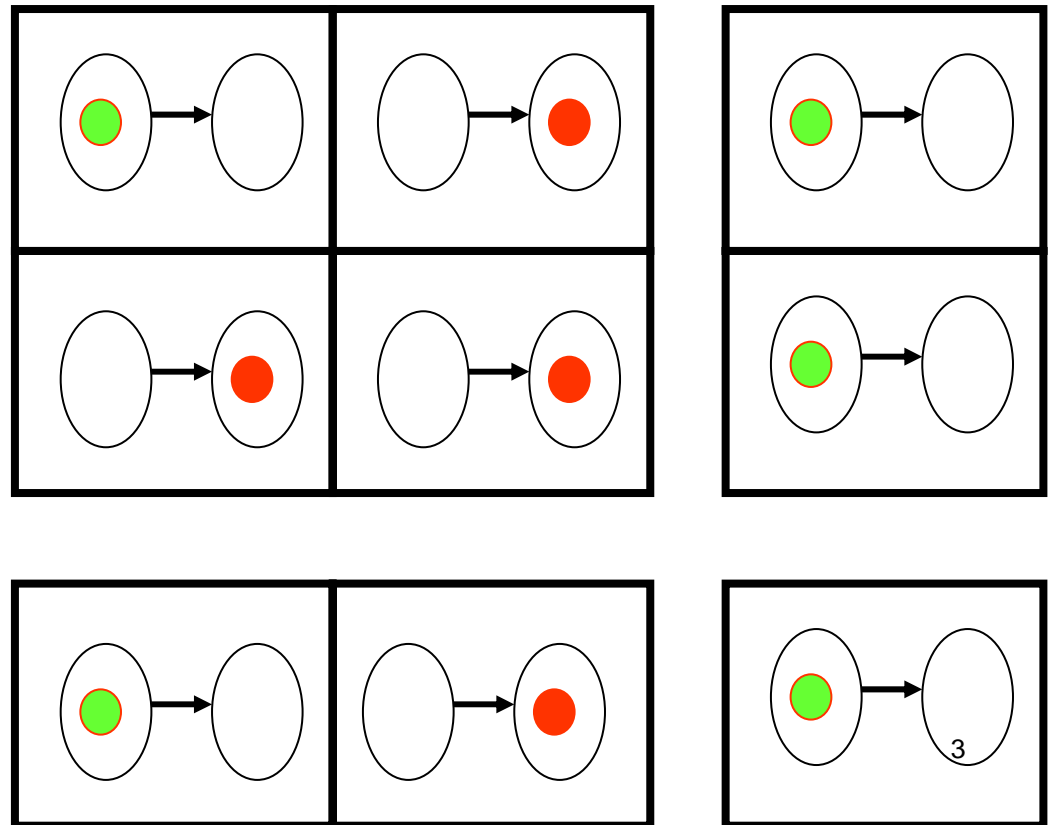


$$IR = cS \quad (I/N) \quad i$$

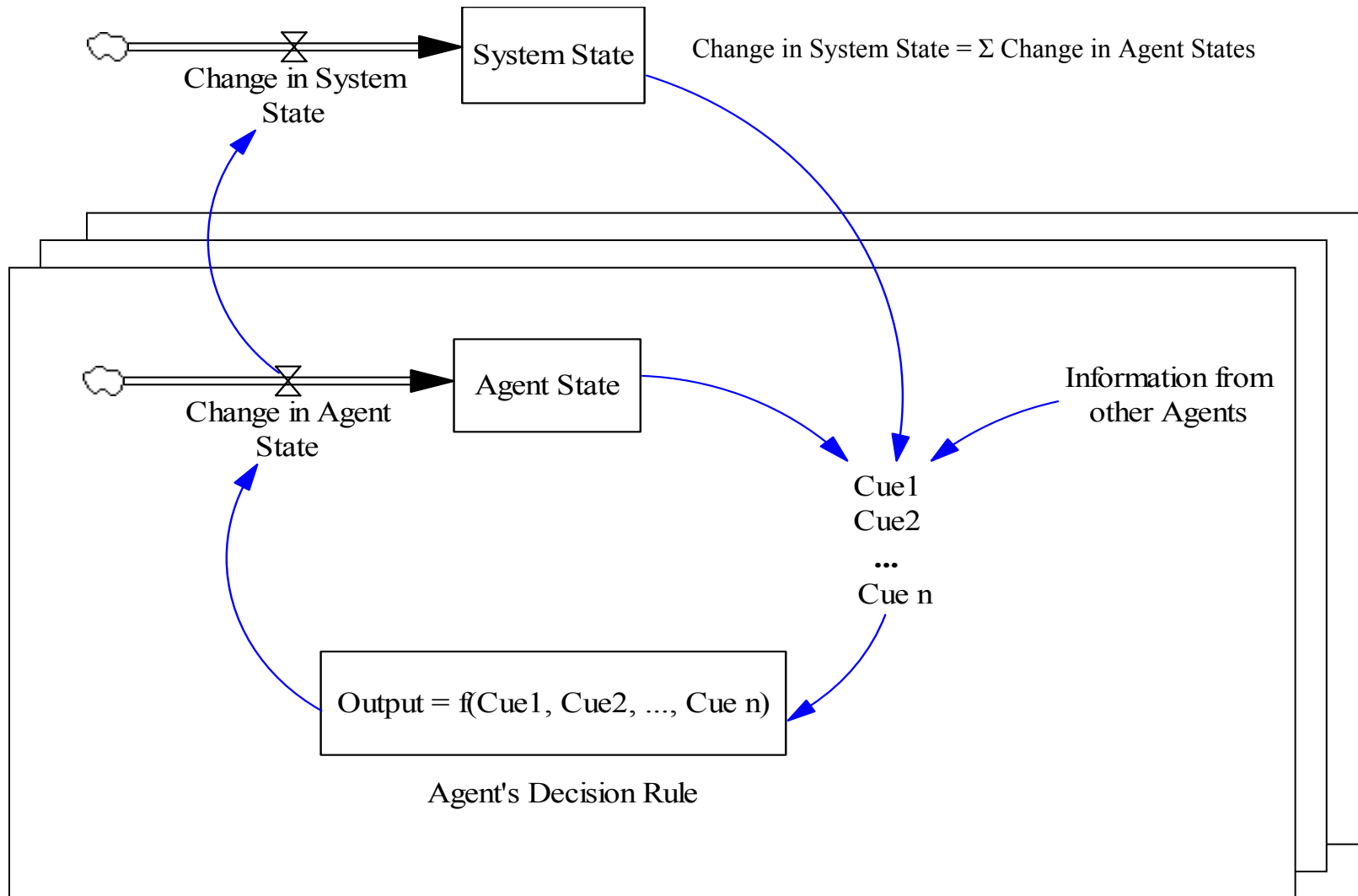
Disaggregate



$$IR = \sum IR_i$$

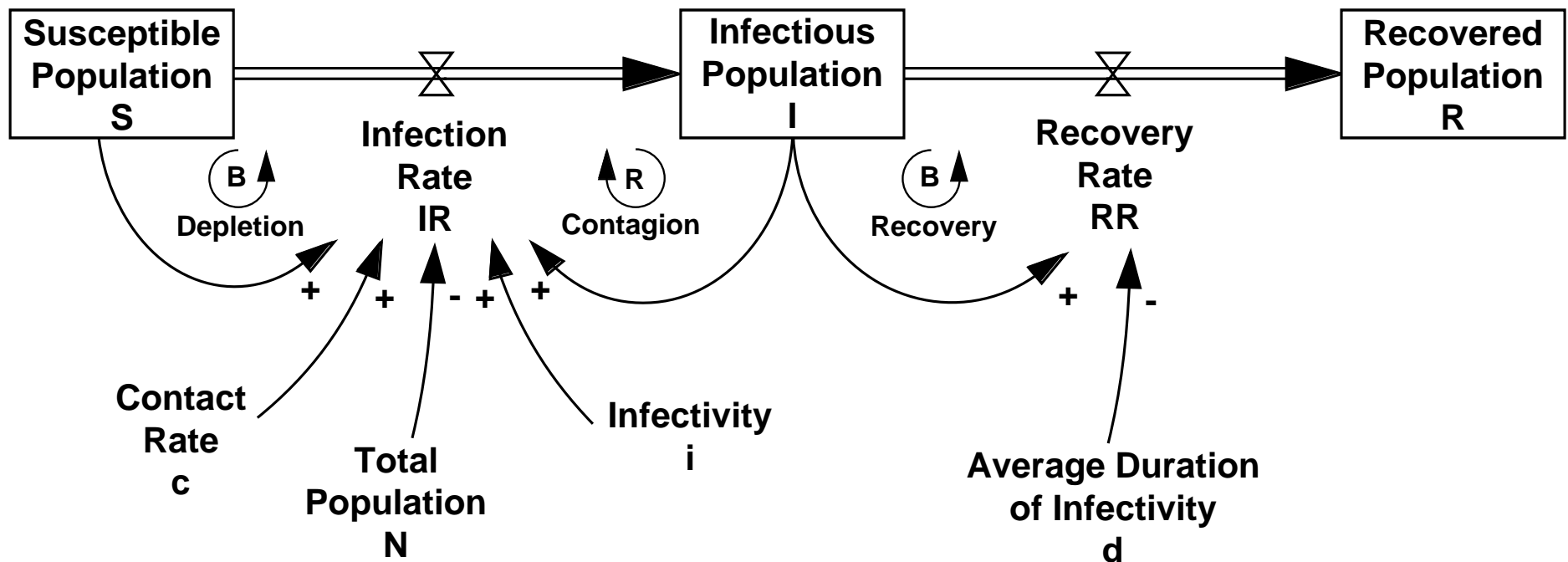
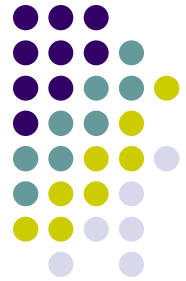


Solution Approach



Different Models Capture Heterogeneity

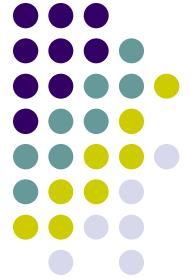
Case Study (SIR) – Classic Model



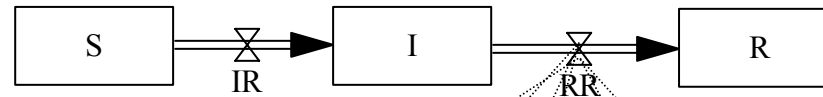
$$IR = cS \left(\frac{I}{N} \right) i$$

$$RR = I/d$$

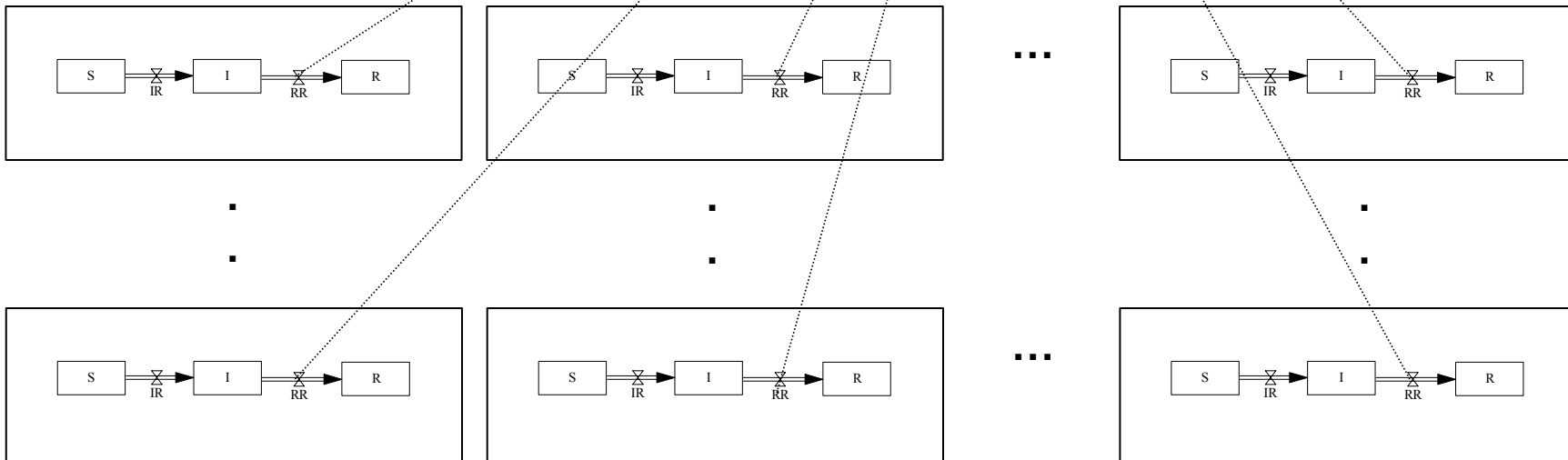
CABM Approach



Aggregate Level

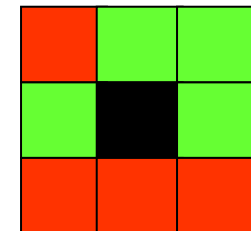
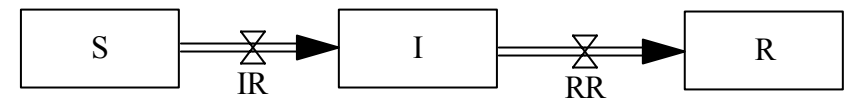


Agent Level



Agent Level

- Sum of stocks = 1
- $RR = \text{DELAYFIXED}$ (IR, Recovery Time)
- IR
 - If $S = 0$, $IR = 0$ else
 - $IR \text{ Prob} = \text{Prop}(I) * \text{Infectivity of Agent}$
 - Generate random number to decide whether to Infect



$$\text{Prop}(I) = 4 / 8 = 0.5$$

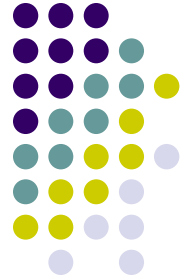
$$\text{Infectivity} = .10$$

$$\text{Prob}(I) = 0.5 * .1 = 0.05$$

$$\text{e.g. } R = .9600$$

If $(1 - R) < 0.05$, then agent is infected,

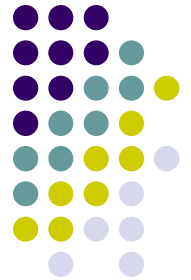
$$IR = 1 / \text{Delta Time}$$



Model Building

- XML-Based
- XML Editor would be useful!
- Three types of files
 - Aggregate Model
 - Agent Models
 - Runtime Model

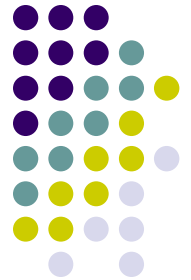
Aggregate Model - Stocks



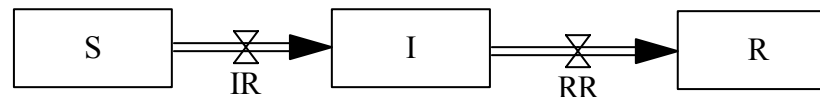
```
<stock>
  <name>Aggregate.Susceptible</name>
  <is_aggregate>true</is_aggregate>
  <init>0.0</init>
  <outflow>Aggregate.InfectionRate</outflow>
</stock>
```

```
  <stock>
    <name>Aggregate.Infected</name>
    <is_aggregate>true</is_aggregate>
    <init>0.0</init>
    <inflow>Aggregate.InfectionRate</inflow>
    <outflow>Aggregate.RecoveryRate</outflow>
  </stock>
```

```
    <stock>
      <name>Aggregate.Recovered</name>
      <is_aggregate>true</is_aggregate>
      <init>0.0</init>
      <inflow>Aggregate.RecoveryRate</inflow>
    </stock>
```

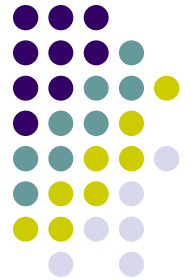


Aggregate Model - Flows



```
<flow>
  <name>Aggregate.InfectionRate</name>
  <is_aggregate>true</is_aggregate>
  <equation>AGGREGATOR() </equation>
</flow>
```

```
<flow>
  <name>Aggregate.RecoveryRate</name>
  <is_aggregate>true</is_aggregate>
  <equation>AGGREGATOR() </equation>
</flow>
```

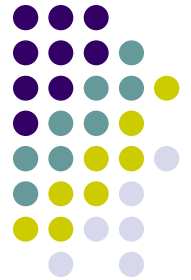


Aggregate Model - Auxs



```
] <auxiliaries>
]   <auxiliary>
    <name>Aggregate.TimeStep</name>
    <equation>TIME_STEP() </equation>
-   </auxiliary>

]   <auxiliary>
    <name>Aggregate.Population</name>
    <equation>Aggregate.Susceptible+Aggregate.Infected+Aggregate.Recovered</equation>
-   </auxiliary>
- </auxiliaries>
```



Agent Model: Stock



<stock>

<name>\$NAME\$.Susceptible</name>

<is_substock>true</is_substock>

<super_stock>Aggregate.Susceptible</super_stock>

<init>\$SUSCEPTIBLE_INIT\$</init>

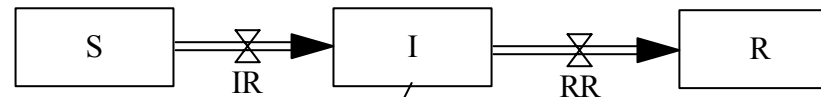
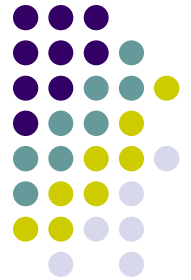
<outflow>\$NAME\$.InfectionRate</outflow>

<capture_state>true</capture_state>

<value_if_true>100</value_if_true>

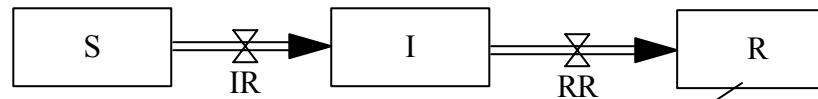
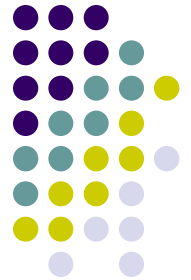
</stock>

Agent Model: Stock



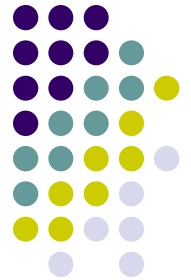
```
<stock>
  <name>$NAME$.Infected</name>
  <is_substock>true</is_substock>
  <super_stock>Aggregate.Infected</super_stock>
  <init>$INFECTED_INIT$</init>
  <inflow>$NAME$.InfectionRate</inflow>
  <outflow>$NAME$.RecoveryRate</outflow>
  <capture_state>true</capture_state>
  <value_if_true>200</value_if_true>
</stock>
```

Agent Model: Stock

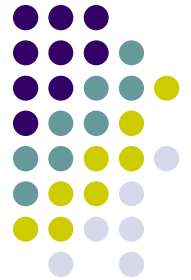


```
<stock>
  <name>$NAME$.Recovered</name>
  <is_substock>true</is_substock>
  <super_stock>Aggregate.Recovered</super_stock>
  <init>$RECOVERED_INIT$</init>
  <inflow>$NAME$.RecoveryRate</inflow>
  <capture_state>true</capture_state>
  <value_if_true>300</value_if_true>
</stock>
```

Agent Model: Flow



```
<flow>
  <name>$NAME$.InfectionRate</name>
  <is_subflow>true</is_subflow>
  <super_flow>Aggregate.InfectionRate</super_flow>
  <equation>EXTERNAL (0) + ($NAME$.NeighboursAvg*0) + ($NAME$.Random*0) </equation>
  <parameter>$NAME$.Susceptible</parameter>
  <parameter>$NAME$.Infectivity</parameter>
  <parameter>$NAME$.NeighboursAvg</parameter>
  <parameter>Aggregate.TimeStep</parameter>
  <parameter>$NAME$.Random</parameter>
</flow>
```



External Function (1)

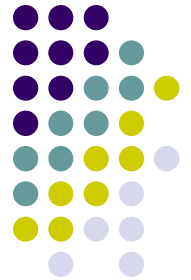
```
override public double ExecuteFunction(String[] parameters, double[] values,
                                       double time)
{
    // value[0] ... susceptible state [either 0 or 1]
    // value[1] ... infectivity (how prone is agent to catching infection
    // value[2] ... neighbourhood average
    // value[3] ... delta time
    // value[4] ... 0..1 random number

    double overallProb = values[1] * values[2];

    if (values[0] > 0.1) // i.e. the agent is susceptible
    {
        if (overallProb >= 1.0 - values[4])
        {
            double ans = 1.0 / values[3];
            return ans;
        }
    }

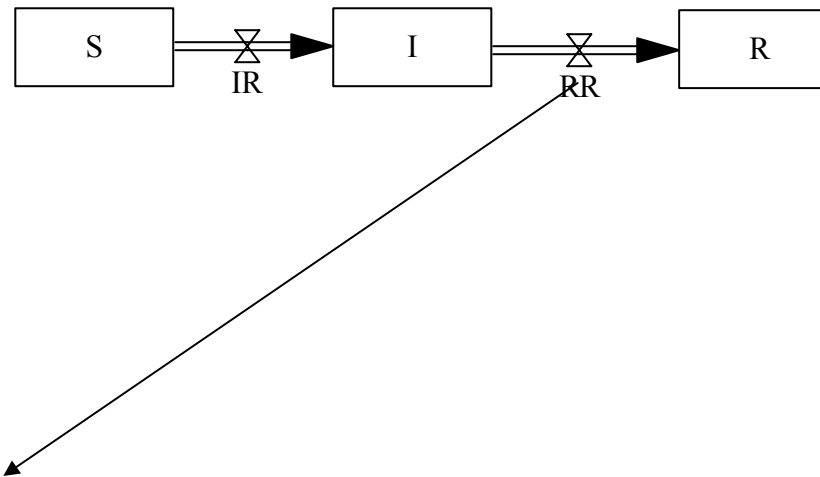
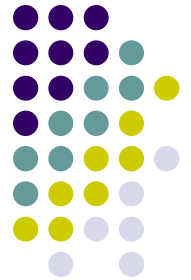
    return 0.0;
}
```


External Function (2)

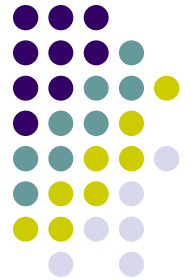


```
<externals>
  <external>
    <id>0</id>
    <path>C:\Program Files\SDPrototype\CSharp</path>
    <assembly>SIRDynamics.dll</assembly>
    <classname>SIRDynamics.GetInfectionRate</classname>
  </external>
</externals>
```

Agent Model: Flow



```
<flow>
  <name>$NAME$.RecoveryRate</name>
  <is_subflow>true</is_subflow>
  <super_flow>Aggregate.RecoveryRate</super_flow>
  <equation>DELAYFIXED($NAME$.InfectionRate, $NAME$.RecoveryDelay,0)</equation>
</flow>
```



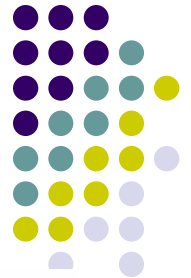
Agent Model: Auxs

```
<auxiliary>
  <name>$NAME$.RecoveryDelay</name>
  <equation>$RECOVERY_DELAY$</equation>
</auxiliary>
```

```
<auxiliary>
  <name>$NAME$.Infectivity</name>
  <equation>$INFECTIVITY_CONSTANT$</equation>
</auxiliary>
```

```
<auxiliary>
  <name>$NAME$.NeighboursAvg</name>
  <equation>NEIGHBOURHOOD_AVERAGE($NAME$, $NAME$.Infected)</equation>
</auxiliary>
```

```
<auxiliary>
  <name>$NAME$.Random</name>
  <equation>RANDOM()</equation>
</auxiliary>
```



Runtime Model - Setup

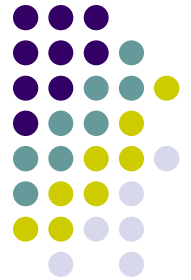
```
<start_time>0</start_time>
<finish_time>20</finish_time>
<time_step>0.25</time_step>
<number_agents>100</number_agents>

<society_structure>Grid</society_structure>
<number_rows>10</number_rows>
<number_columns>10</number_columns>

<do_grid_trace>true</do_grid_trace>
<grid_state_variables>
  <grid_state_variable>Susceptible</grid_state_variable>
  <grid_state_variable>Infected</grid_state_variable>
  <grid_state_variable>Recovered</grid_state_variable>
</grid_state_variables>

<grid_trace_frequency>5</grid_trace_frequency>
```

Runtime Model – Aggregate and Sub Models



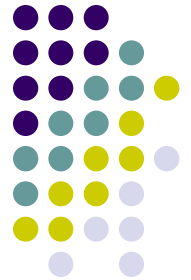
```
<aggregate_model_name>AggregateModel.xml</aggregate_model_name>
<aggregate_model_path>C:\Program Files\SDPrototype\Models\CABM\SDS_07_Workshop\
</aggregate_model_path>

<submodels>
  <submodel>
    <id>0</id>
    <file>TestAgent_01.xml</file>
    <path>C:\Program Files\SDPrototype\Models\CABM\SDS_07_Workshop\</path>
  </submodel>

  <submodel>
    <id>1</id>
    <file>TestAgent_02.xml</file>
    <path>C:\Program Files\SDPrototype\Models\CABM\SDS_07_Workshop\</path>
  </submodel>

</submodels>
```

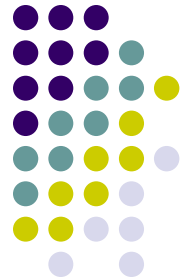
Runtime Model – Agent Instances



```
<agent_instances>
  <agent_instance>
    <id>NormalAgentSusceptible</id>
    <percentage>95</percentage>
  </agent_instance>

  <agent_instance>
    <id>NormalAgentInfected</id>
    <percentage>5</percentage>
  </agent_instance>

</agent_instances>
```



```
<segment>
  <segment_id>NormalAgentSusceptible</segment_id>
  <submodel_id>1</submodel_id>|
  <parameters>
    <parameter>
      <id>$SUSCEPTIBLE_INIT$</id>
      <value>1</value>
    </parameter>

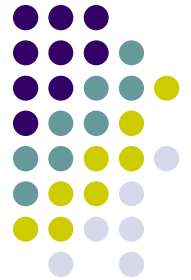
    <parameter>
      <id>$INFECTED_INIT$</id>
      <value>0</value>
    </parameter>

    <parameter>
      <id>$RECOVERED_INIT$</id>
      <value>0</value>
    </parameter>

    <parameter>
      <id>$RECOVERY_DELAY$</id>
      <value>3</value>
    </parameter>

    <parameter>
      <id>$INFECTIVITY_CONSTANT$</id>
      <value>0.15</value>
    </parameter>
  </parameters>
</segment>
```

Runtime Model – Agent Type 1



```
<segment>
  <segment_id>NormalAgentInfected</segment_id>
  <submodel_id>1</submodel_id>
  <parameters>
    <parameter>
      <id>$SUSCEPTIBLE_INIT$</id>
      <value>0</value>
    </parameter>

    <parameter>
      <id>$INFECTED_INIT$</id>
      <value>1</value>
    </parameter>

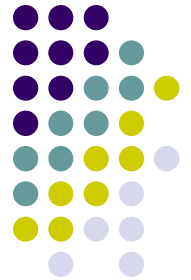
    <parameter>
      <id>$RECOVERED_INIT$</id>
      <value>0</value>
    </parameter>

    <parameter>
      <id>$RECOVERY_DELAY$</id>
      <value>3</value>
    </parameter>

    <parameter>
      <id>$INFECTIVITY_CONSTANT$</id>
      <value>0.15</value>
    </parameter>
  </parameters>
</segment>
```

Runtime Model – Agent Type 2

CABM.exe.config



```
<?xml version="1.0" encoding="utf-8" ?>
<configuration>
  <appSettings>
    <add key="InputFile" value="RunTimeModel.xml" />
    <add key="OutputFile" value="RunTimeBenchmarkModel.xml" />
    <add key="InputDirectory" value="C:\Program Files\SDPrototype\Models\CABM\SDS_07_Workshop\" />
    <add key="OutputDirectorySim" value="C:\Program Files\SDPrototype\Results\CABM\SDS_07_Workshop\" />
    <add key="FilterOutput" value="true" />
    <add key="NumberFilterVariables" value="4" />
    <add key="FilterVariable_0" value="Aggregate.Susceptible" />
    <add key="FilterVariable_1" value="Aggregate.Infected" />
    <add key="FilterVariable_2" value="Aggregate.Recovered" />
    <add key="FilterVariable_3" value="Aggregate.Population" />
  </appSettings>
</configuration>
```

Run Simulation (CABM)



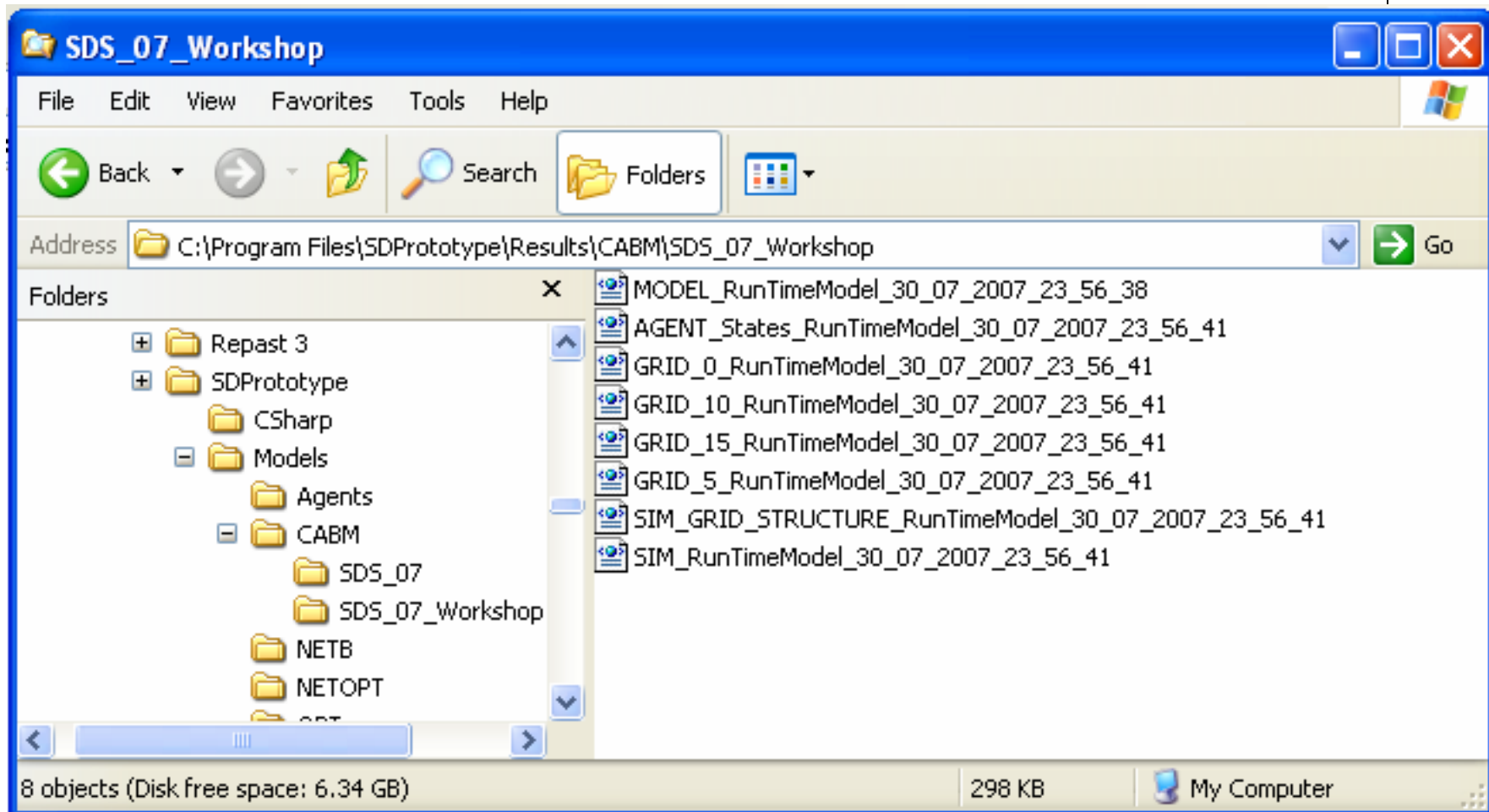
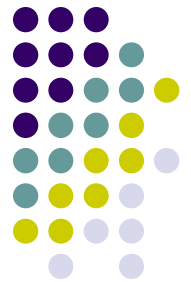
```
C:\WINDOWS\system32\cmd.exe
C:\Program Files\SDPrototype>
C:\Program Files\SDPrototype>
C:\Program Files\SDPrototype>cabm

CABM U1.0... running [RunTimeModel.xml] @ time [30/07/2007 23:49:33]
Reading the contents from the file[C:\Program Files\SDPrototype\Models\CABM\SDS_
07_Workshop\RunTimeModel.xml]
Is_Sensitivity = False #agents = 100

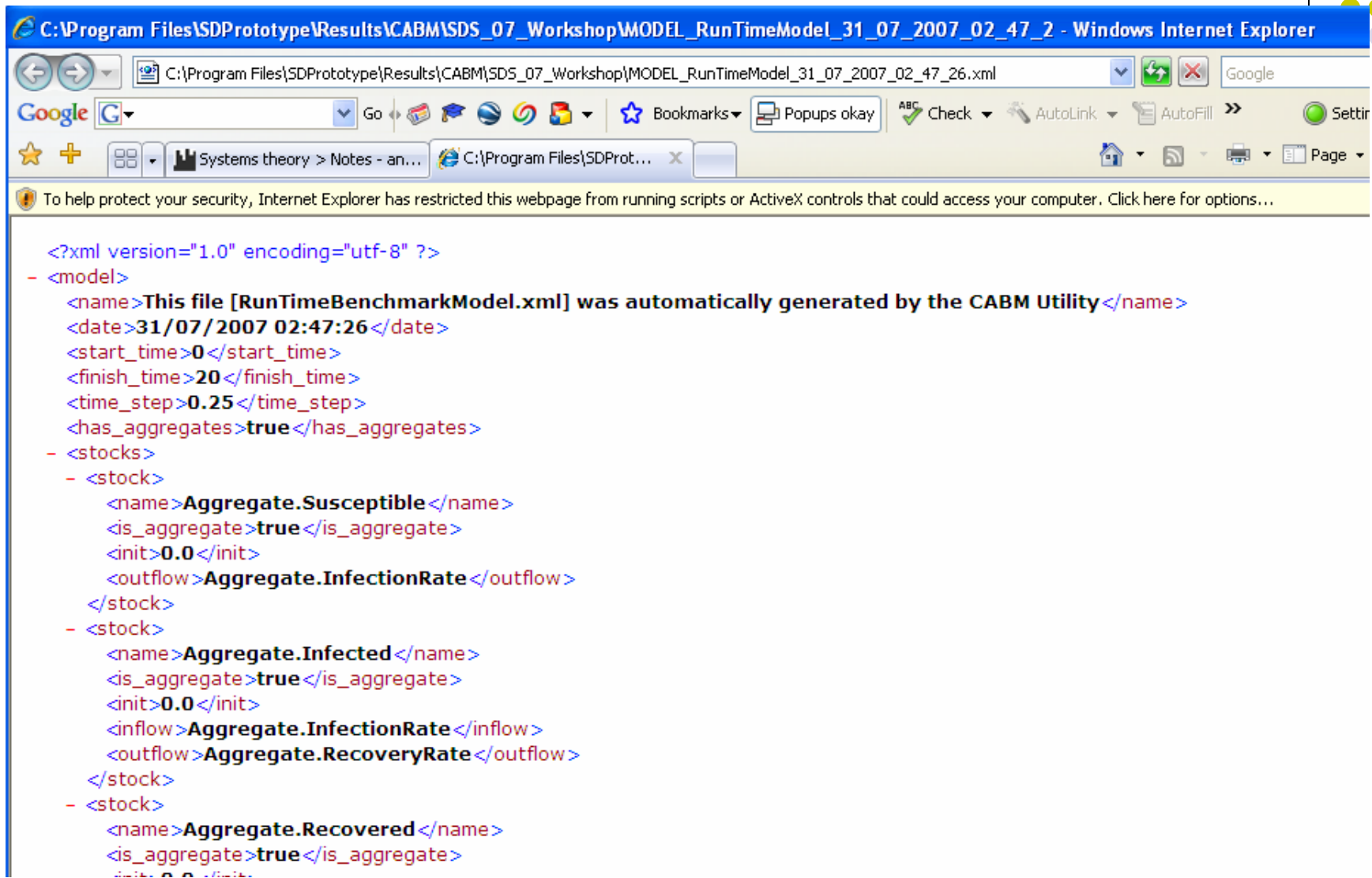
Reading the contents from the file[C:\Program Files\SDPrototype\Models\CABM\SDS_
07_Workshop\AggregateModel.xml]
Reading the contents from the file[C:\Program Files\SDPrototype\Models\CABM\SDS_
07_Workshop\TestAgent.xml]
Starting Agent Simulation run
>>> C:\Program Files\SDPrototype\Results\CABM\SDS_07_Workshop\MODEL_RunTimeModel
_30_07_2007_23_49_33.xml
Starting Integration @ [30/07/2007 23:49:33.695]
Finished Integration @ [30/07/2007 23:49:35.617]
CABM... [XML] results written to directory [C:\Program Files\SDPrototype\Results
\CABM\SDS_07_Workshop\]
CABM U1.0... Completed @ time [30/07/2007 23:49:35]

C:\Program Files\SDPrototype>
```

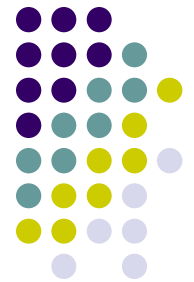
XML Output Files



The Full Model: Model_RuntimeModel



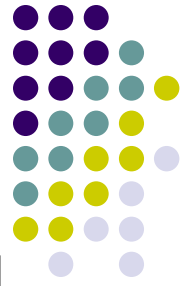
```
<?xml version="1.0" encoding="utf-8" ?>
- <model>
  <name>This file [RunTimeBenchmarkModel.xml] was automatically generated by the CABM Utility</name>
  <date>31/07/2007 02:47:26</date>
  <start_time>0</start_time>
  <finish_time>20</finish_time>
  <time_step>0.25</time_step>
  <has_aggregates>true</has_aggregates>
- <stocks>
  - <stock>
    <name>Aggregate.Susceptible</name>
    <is_aggregate>true</is_aggregate>
    <init>0.0</init>
    <outflow>Aggregate.InfectionRate</outflow>
  </stock>
  - <stock>
    <name>Aggregate.Infected</name>
    <is_aggregate>true</is_aggregate>
    <init>0.0</init>
    <inflow>Aggregate.InfectionRate</inflow>
    <outflow>Aggregate.RecoveryRate</outflow>
  </stock>
  - <stock>
    <name>Aggregate.Recovered</name>
    <is_aggregate>true</is_aggregate>
```



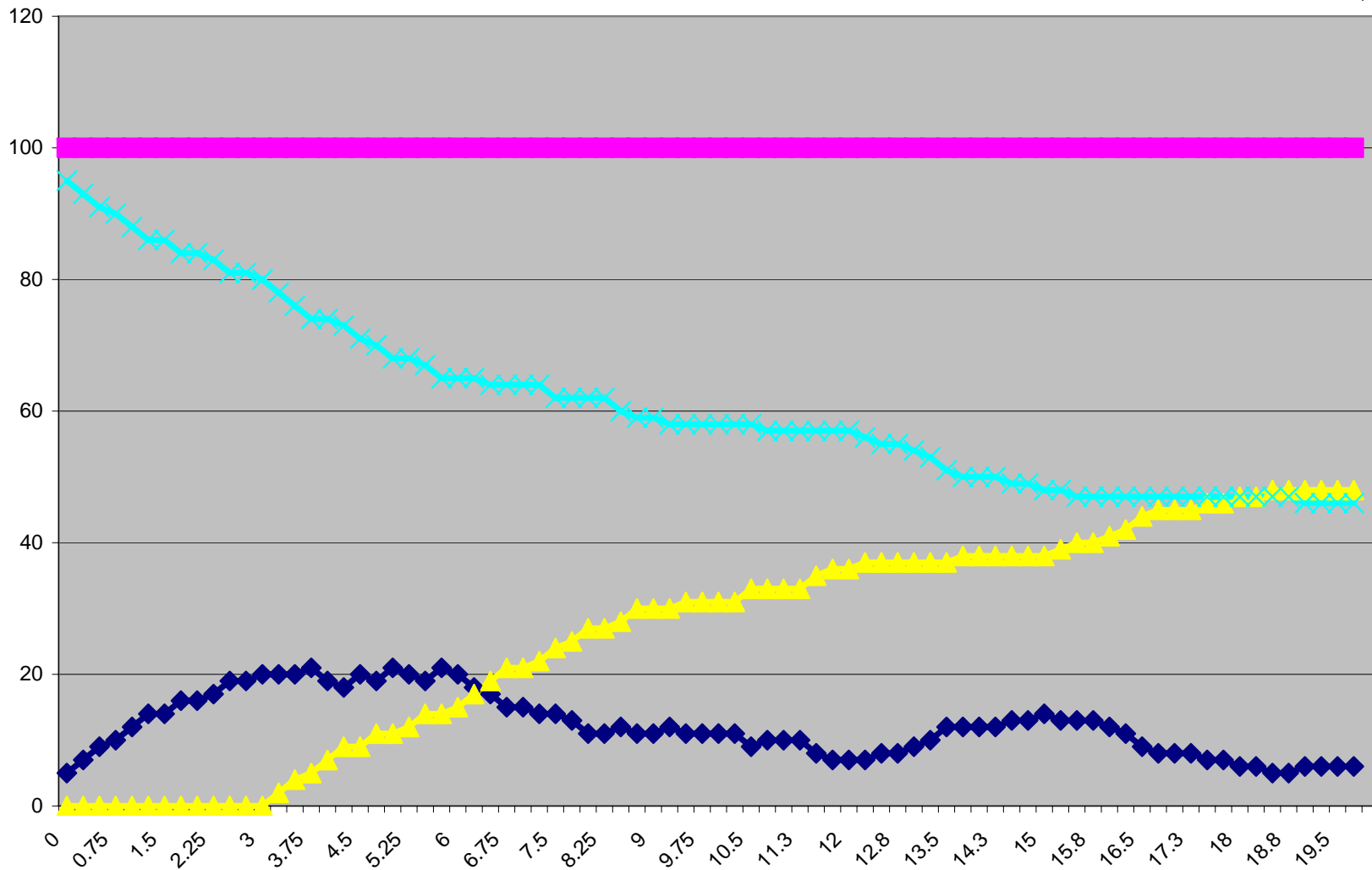
Aggregate Results: SIM_RunTimeModel

| | A | B | C | D | E |
|----|------|--------------------|----------------------|---------------------|-----------------------|
| 1 | Time | Aggregate.Infected | Aggregate.Population | Aggregate.Recovered | Aggregate.Susceptible |
| 2 | 0 | 5 | 100 | 0 | 95 |
| 3 | 0.25 | 7 | 100 | 0 | 93 |
| 4 | 0.5 | 9 | 100 | 0 | 91 |
| 5 | 0.75 | 10 | 100 | 0 | 90 |
| 6 | 1 | 12 | 100 | 0 | 88 |
| 7 | 1.25 | 14 | 100 | 0 | 86 |
| 8 | 1.5 | 14 | 100 | 0 | 86 |
| 9 | 1.75 | 16 | 100 | 0 | 84 |
| 10 | 2 | 16 | 100 | 0 | 84 |
| 11 | 2.25 | 17 | 100 | 0 | 83 |
| 12 | 2.5 | 19 | 100 | 0 | 81 |
| 13 | 2.75 | 19 | 100 | 0 | 81 |
| 14 | 3 | 20 | 100 | 0 | 80 |
| 15 | 3.25 | 20 | 100 | 2 | 78 |
| 16 | 3.5 | 20 | 100 | 4 | 76 |
| 17 | 3.75 | 21 | 100 | 5 | 74 |
| 18 | 4 | 19 | 100 | 7 | 74 |
| 19 | 4.25 | 18 | 100 | 9 | 73 |
| 20 | 4.5 | 20 | 100 | 9 | 71 |
| 21 | 4.75 | 19 | 100 | 11 | 70 |
| 22 | 5 | 21 | 100 | 11 | 68 |

Aggregate Results: SIM_RunTimeModel



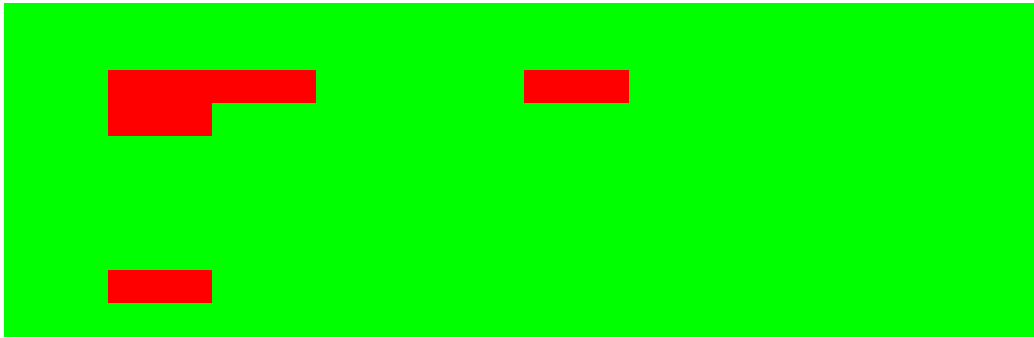
Aggregate.Infected Aggregate.Population Aggregate.Recovered Aggregate.Susceptible



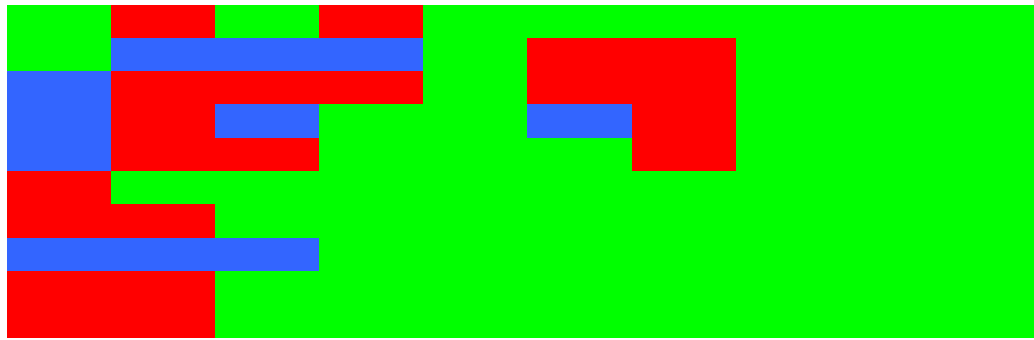


GRID_Structure

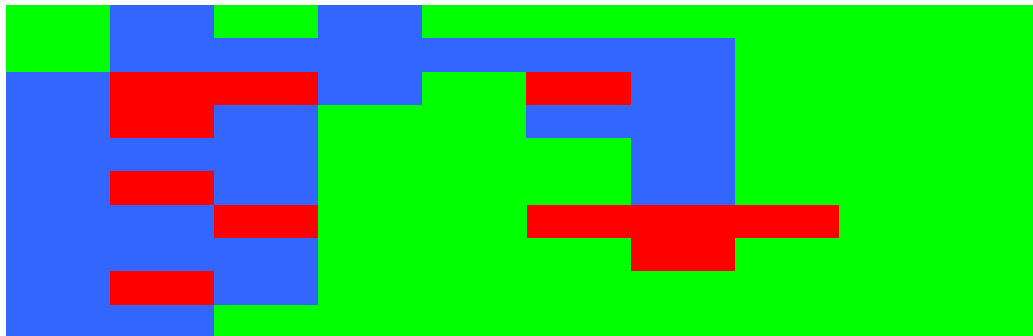
| | A | B | C | D |
|----|------|-------|----------|------------------------------|
| 1 | ID ▼ | row ▼ | column ▼ | agent ▼ |
| 2 | 1 | 0 | 0 | NormalAgentSusceptible_AG_63 |
| 3 | 1 | 0 | 1 | NormalAgentSusceptible_AG_65 |
| 4 | 1 | 0 | 2 | NormalAgentSusceptible_AG_2 |
| 5 | 1 | 0 | 3 | NormalAgentSusceptible_AG_55 |
| 6 | 1 | 0 | 4 | NormalAgentSusceptible_AG_61 |
| 7 | 1 | 0 | 5 | NormalAgentSusceptible_AG_72 |
| 8 | 1 | 0 | 6 | NormalAgentSusceptible_AG_92 |
| 9 | 1 | 0 | 7 | NormalAgentSusceptible_AG_57 |
| 10 | 1 | 0 | 8 | NormalAgentSusceptible_AG_52 |
| 11 | 1 | 0 | 9 | NormalAgentSusceptible_AG_83 |
| 12 | 1 | 1 | 0 | NormalAgentSusceptible_AG_7 |
| 13 | 1 | 1 | 1 | NormalAgentSusceptible_AG_30 |
| 14 | 1 | 1 | 2 | NormalAgentSusceptible_AG_68 |
| 15 | 1 | 1 | 3 | NormalAgentSusceptible_AG_45 |
| 16 | 1 | 1 | 4 | NormalAgentSusceptible_AG_18 |
| 17 | 1 | 1 | 5 | NormalAgentSusceptible_AG_80 |
| 18 | 1 | 1 | 6 | NormalAgentSusceptible_AG_32 |
| 19 | 1 | 1 | 7 | NormalAgentSusceptible_AG_86 |
| 20 | 1 | 1 | 8 | NormalAgentSusceptible_AG_62 |
| 21 | 1 | 1 | 9 | NormalAgentSusceptible_AG_15 |
| 22 | 1 | 2 | 0 | NormalAgentSusceptible_AG_66 |



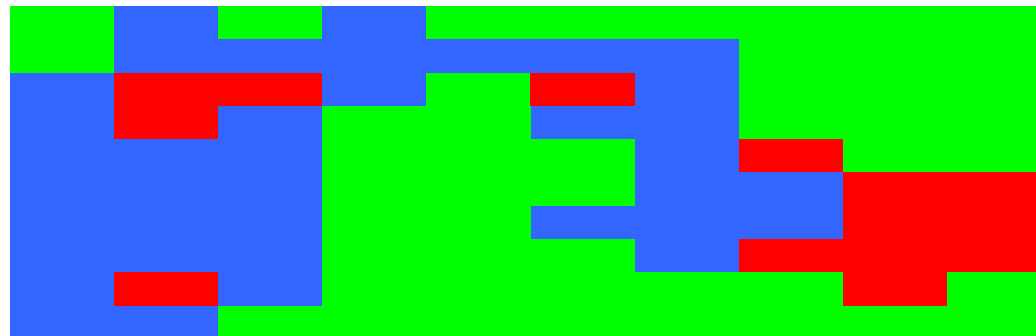
t = 0



t = 5

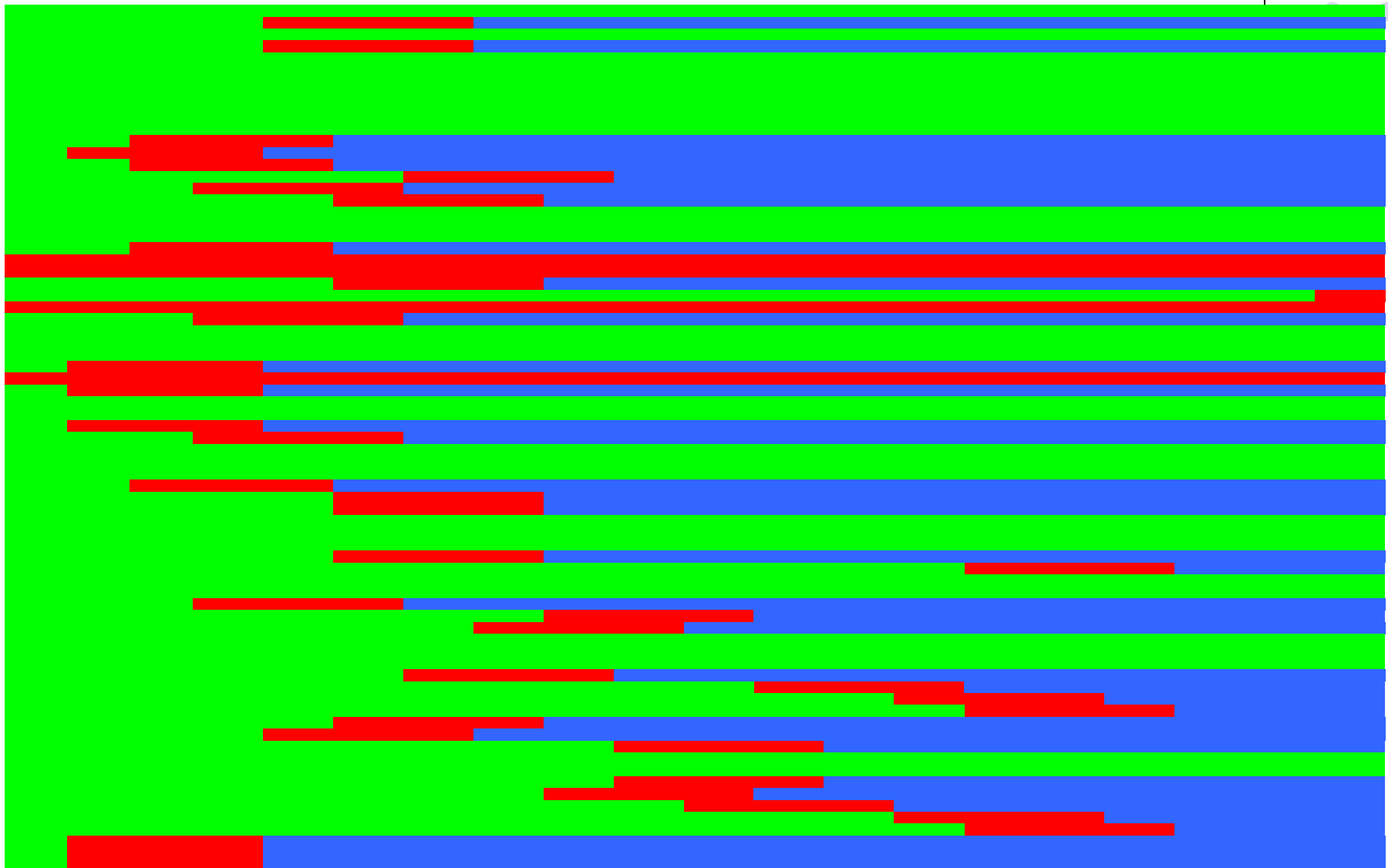
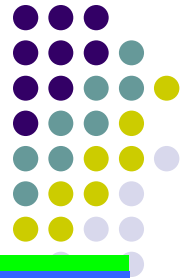


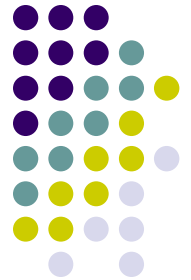
t = 10



t = 15

Agent State Changes





Conclusions

- An exploratory approach to use SD as a basis ABM
- Research applications, and classroom teaching
- Enhancements:
 - Underlying network structures
 - Usability
 - Performance
 - Aggregating mechanisms

