Overview of the Simulation Modeling Process

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CMPT 858

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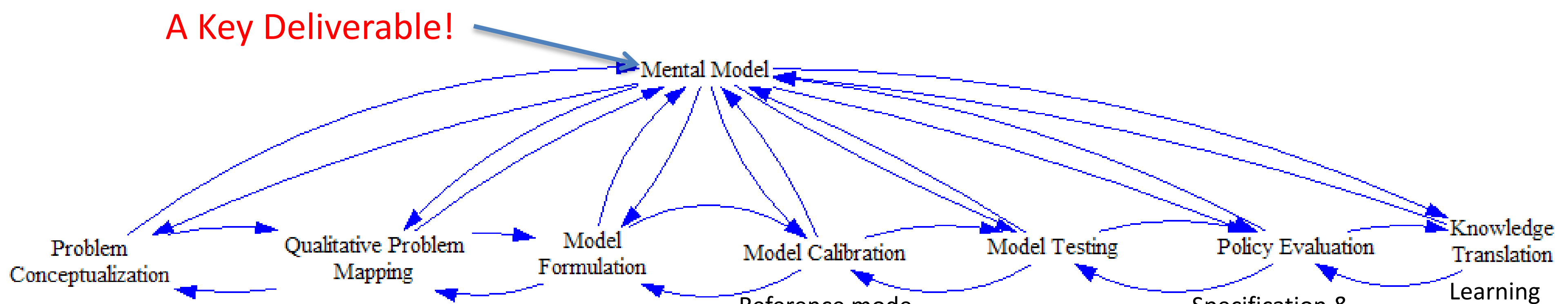
Announcements

- Tutorial vote link sent
  - Please vote by Wednesday evening
- Download & install Vensim PLE
  - http://www.vensim.com/freedownload.html

Overview of Modeling Process

- Typically conducted with an interdisciplinary team
- An ongoing process of refinement
- Best: Iteration with modeling, intervention implementation, data collection
- Often it is the *modeling process* itself – rather than the models created – that offers the greatest value

Modeling Process Overview



Model scope/boundary selection.

Model time horizon
Identification of

Key variables

Reference modes for explanation

Causal loop diagrams

State charts

System Structure diagrams

Multi-agent interaction diagrams

Multi-scale hierarchy diagrams

Process flow structure

Specification of

- Parameters
- Quantitative causal relations
- Decision/behavior rules
- Initial conditions

Reference mode reproduction

Matching of intermediate time series

Matching of observed data points

Constrain to sensible bounds
Structural sensitivity analysis

Parameter sensitivity analysis

Cross-validation

Robustness&extreme value tests

Unit checking
Problem domain tests

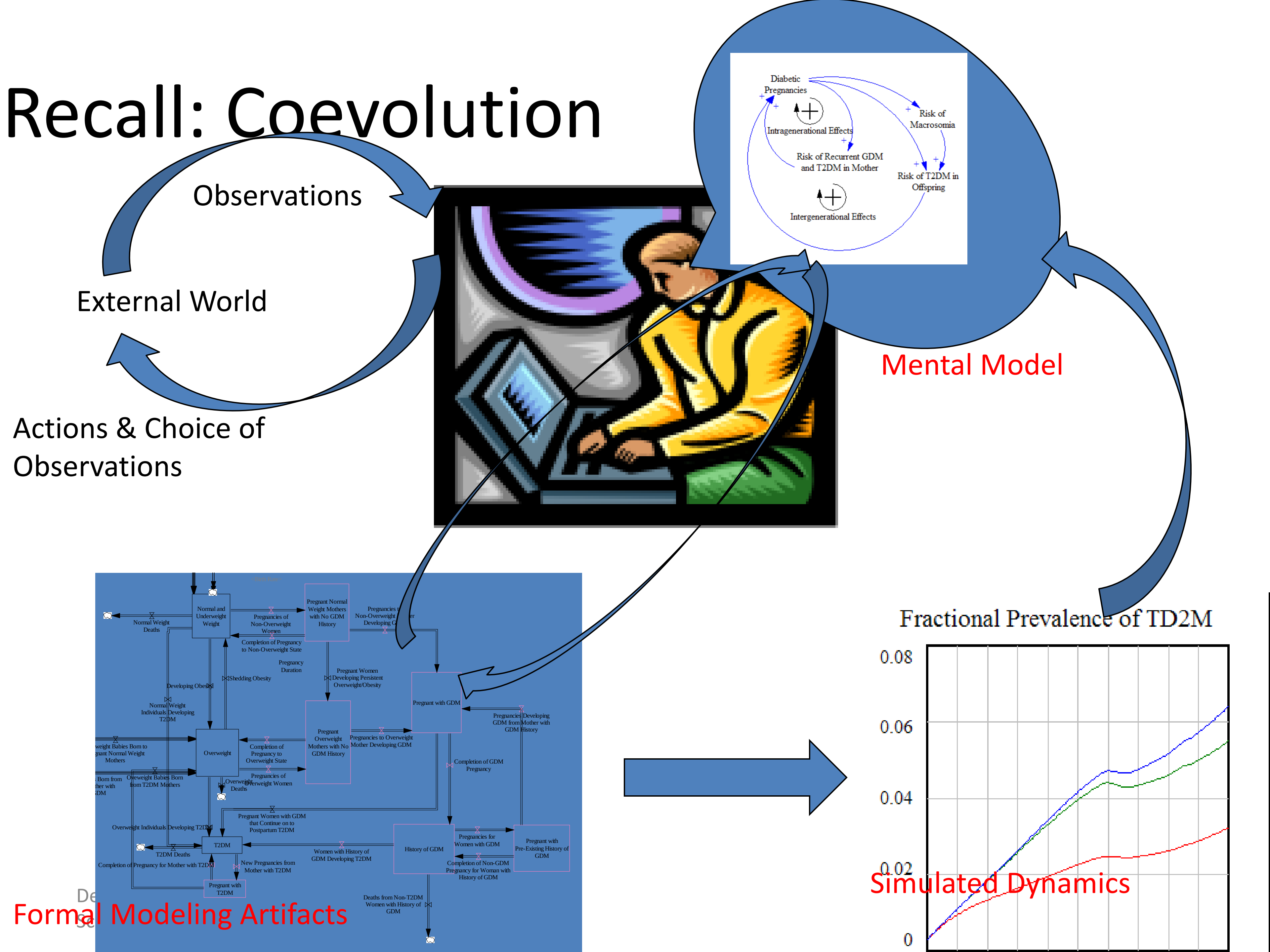
Specification & investigation of intervention scenarios
Investigation of hypothetical external conditions

Cross-scenario comparisons (e.g. CEA)

Learning environments/Microworlds/flight simulators

Group model building

Recall: Coevolution



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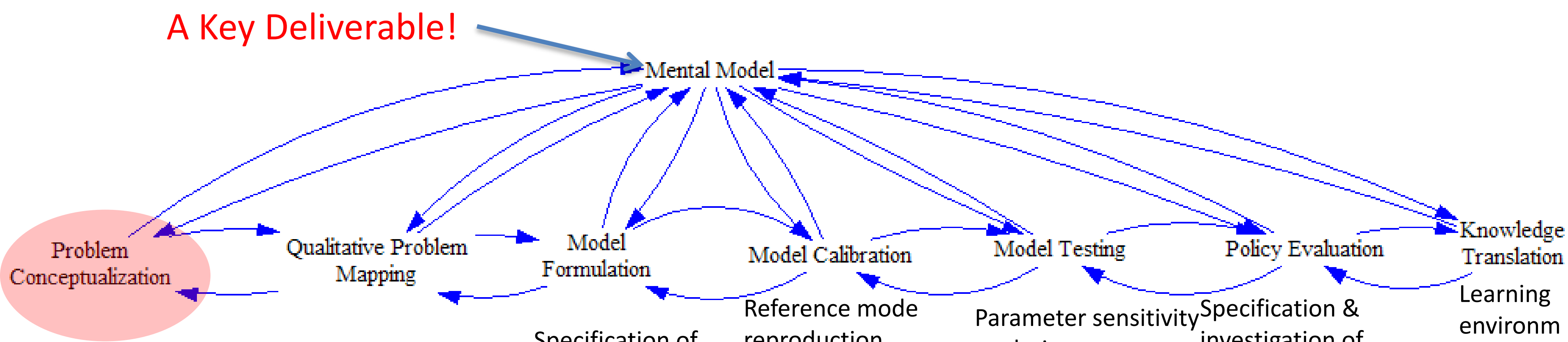

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Identification of Questions/ "The Problem"

- All models are simplifications and "wrong"
- Some models are useful
- Attempts at perfect representation of "real-world" system generally offer little value
- Establishing a clear model purpose is critical for defining what is included in a model
  - Understanding broad trends/insight?
  - Understanding policy impacts?
  - Ruling out certain hypotheses?
- Think explicitly about model boundaries
- Adding factors often does not yield greater insight
  - Often simplest models give greatest insight
  - Opportunity costs: More complex model takes more time to build=>less time for insight

Importance of Purpose

Firmness of purpose is one of the most necessary sinews of character, and one of the best instruments of success. Without it genius wastes its efforts in a maze of inconsistencies.

Lord Chesterfield

The secret of success is constancy of purpose.

Benjamin Disraeli

The art of model building is knowing what to cut out, and the purpose of the model acts as the logical knife. It provides the criterion about what will be cut, so that only the essential features necessary to fulfill the purpose are left.

John Sterman

Common Division

- Endogenous
  - Things whose dynamics are calculated as part of the model
- Exogenous
  - Things that are included in model consideration, but are specified externally
    - Time series
    - Constants
- Ignored/Excluded
  - Things outside the boundary of the model

Example of Boundary Definition

Fiddaman *A Feedback-Rich Climate-Economy Model* (1998)

Table 1: Model Boundary

Endogenous	Exogenous	Excluded
Economic output	Population	Labor mobility and participation
Consumption	Factor productivity	Money stocks and monetary effects
Interest rates	Autonomous energy efficiency improvement	Non-energy resources
Investment	Oil/gas and coal prices (1960-1990)	Regional disaggregation
Embodiment of energy requirements in capital	Nonenergy CO_2 emissions	Sectoral disaggregation (other than energy)
Energy prices	Greenhouse gases other than CO_2	Fossil-fired electric power generation
Energy production		Inventories and backlogs
Energy technology		
Depletion		
CO_2 Emissions		
Carbon Cycle		
Atmosphere and ocean temperature		
Climate damages		

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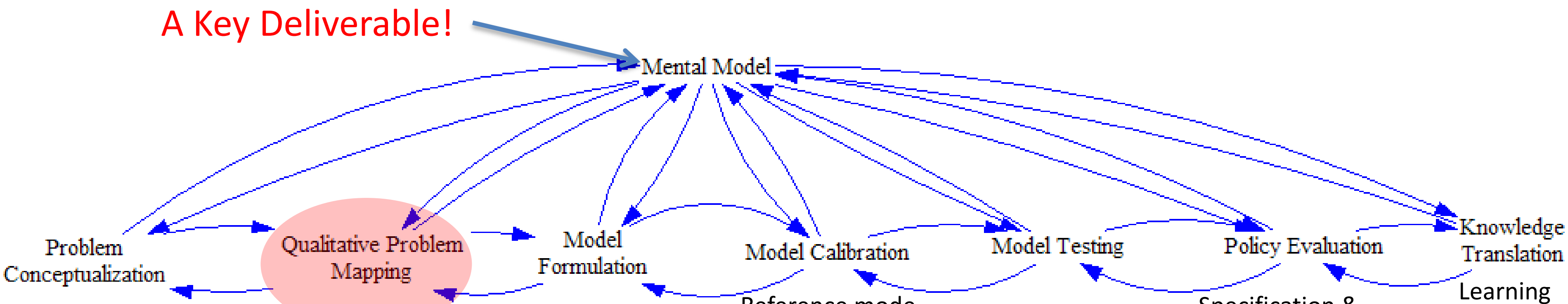

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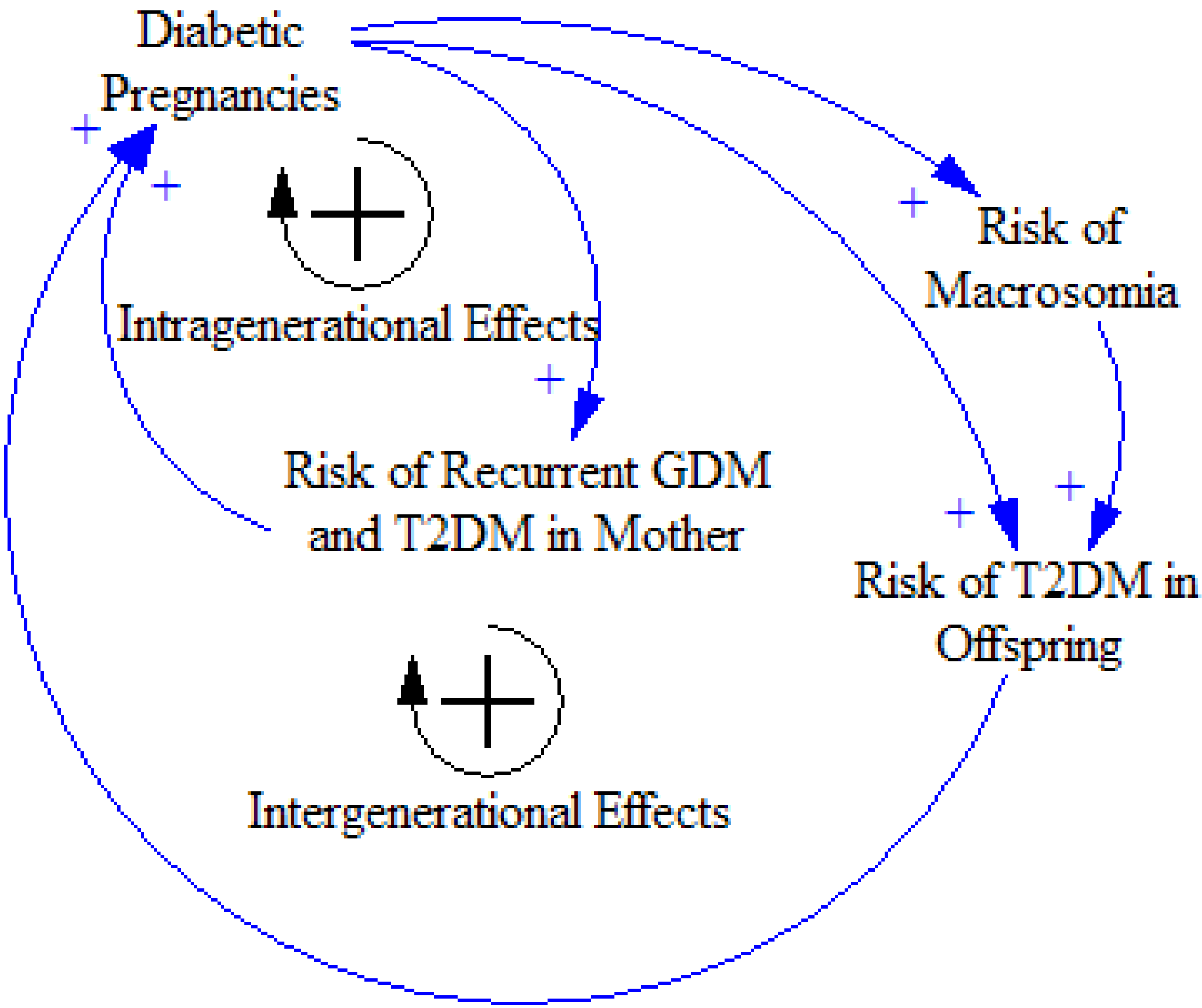
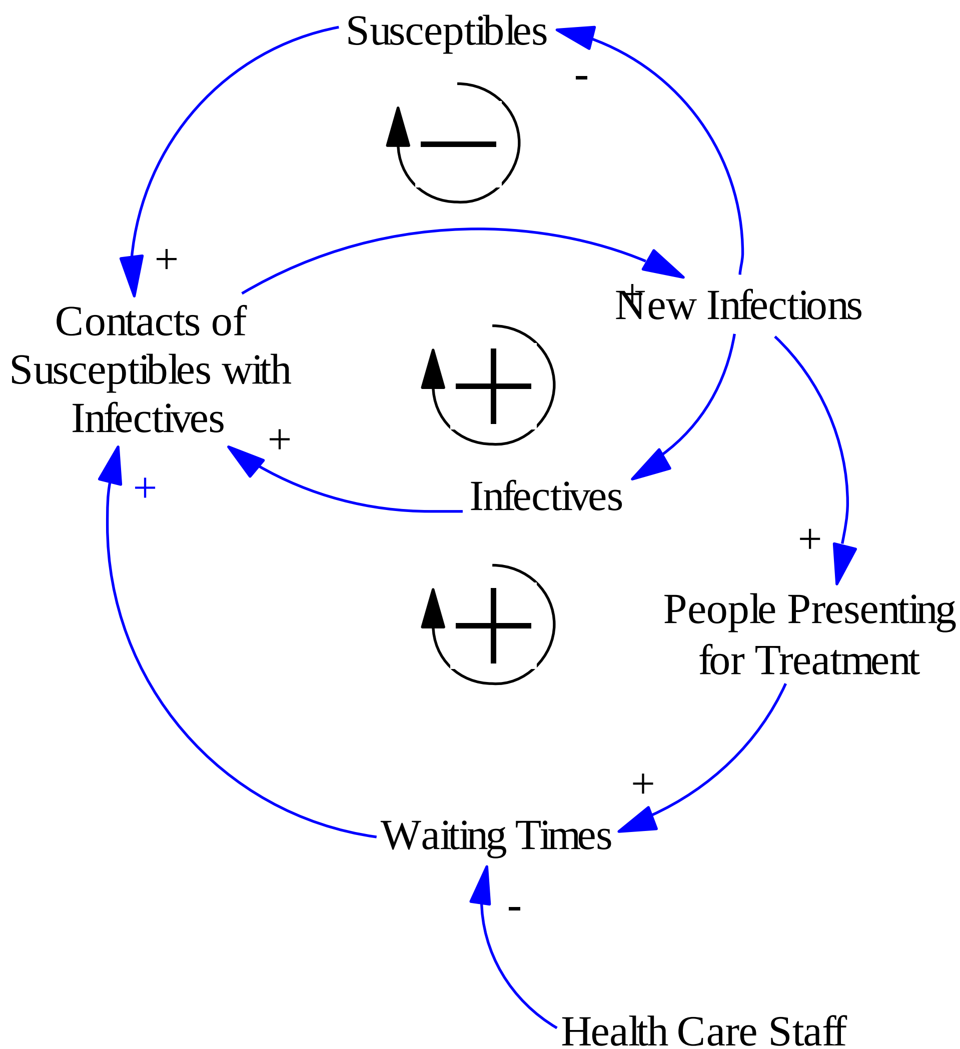
Example Causal Loop Diagram

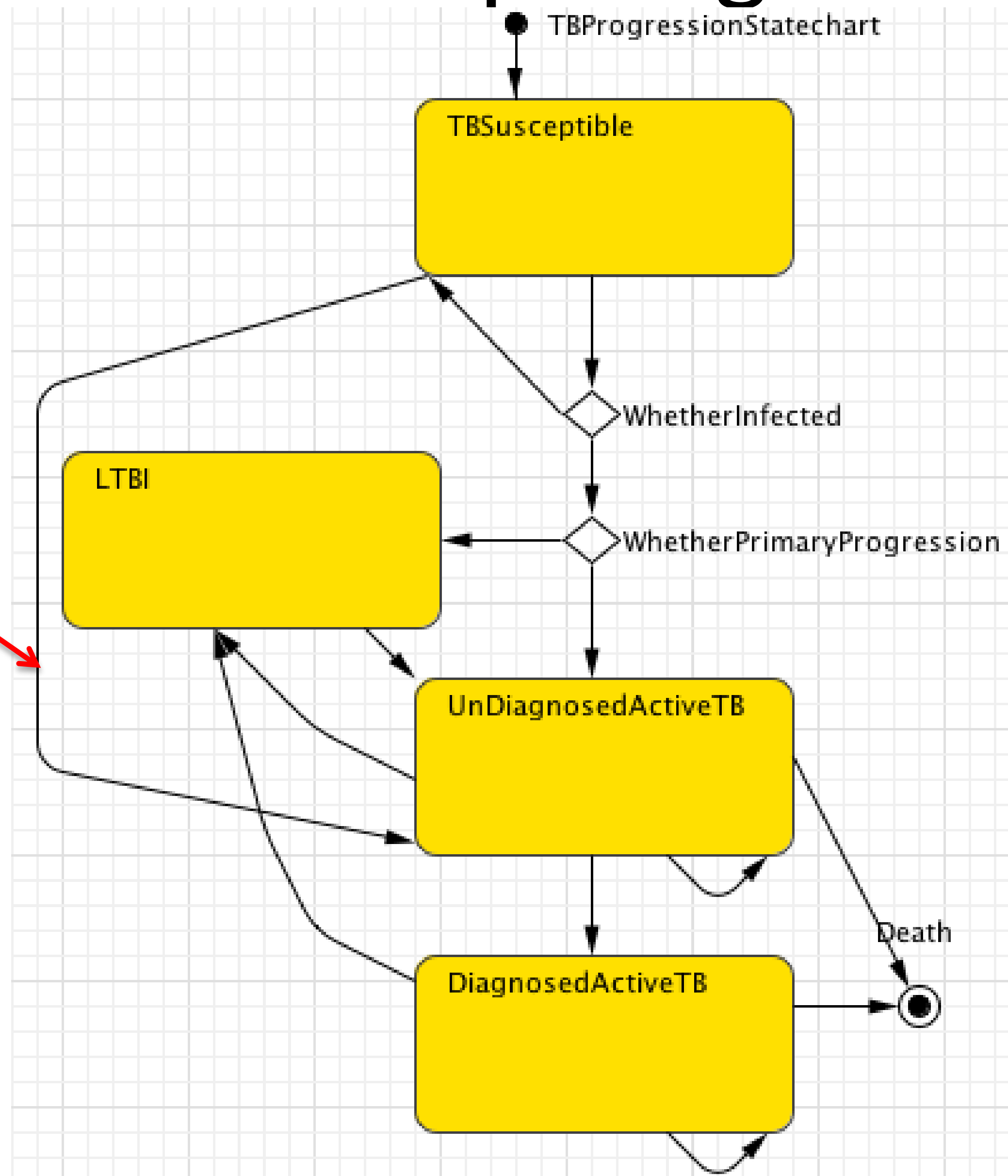


A Second Causal Loop Diagram

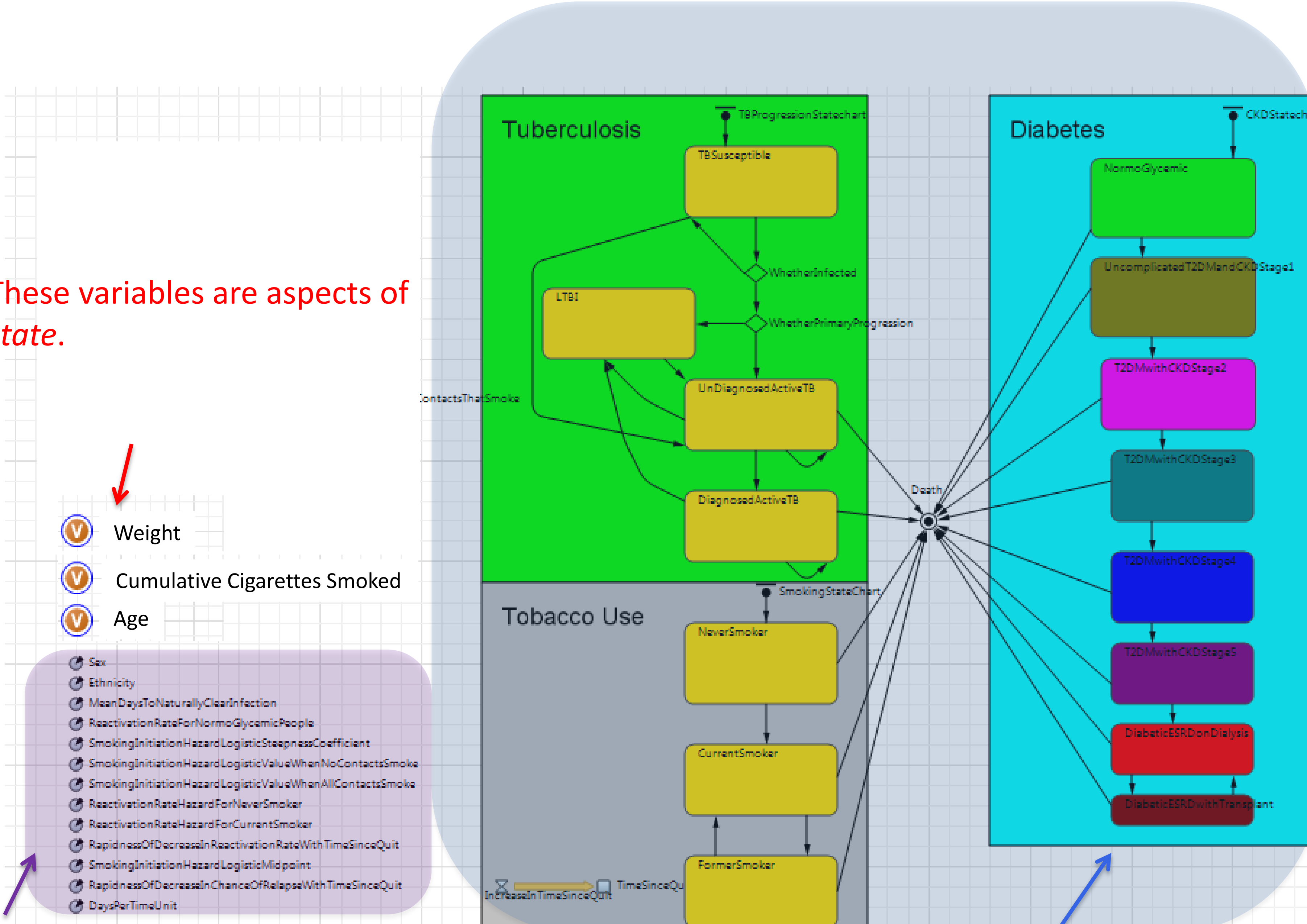


Qualitative Causal Loop Diagram

Qualitative Transitions (no likelihood yet specified)



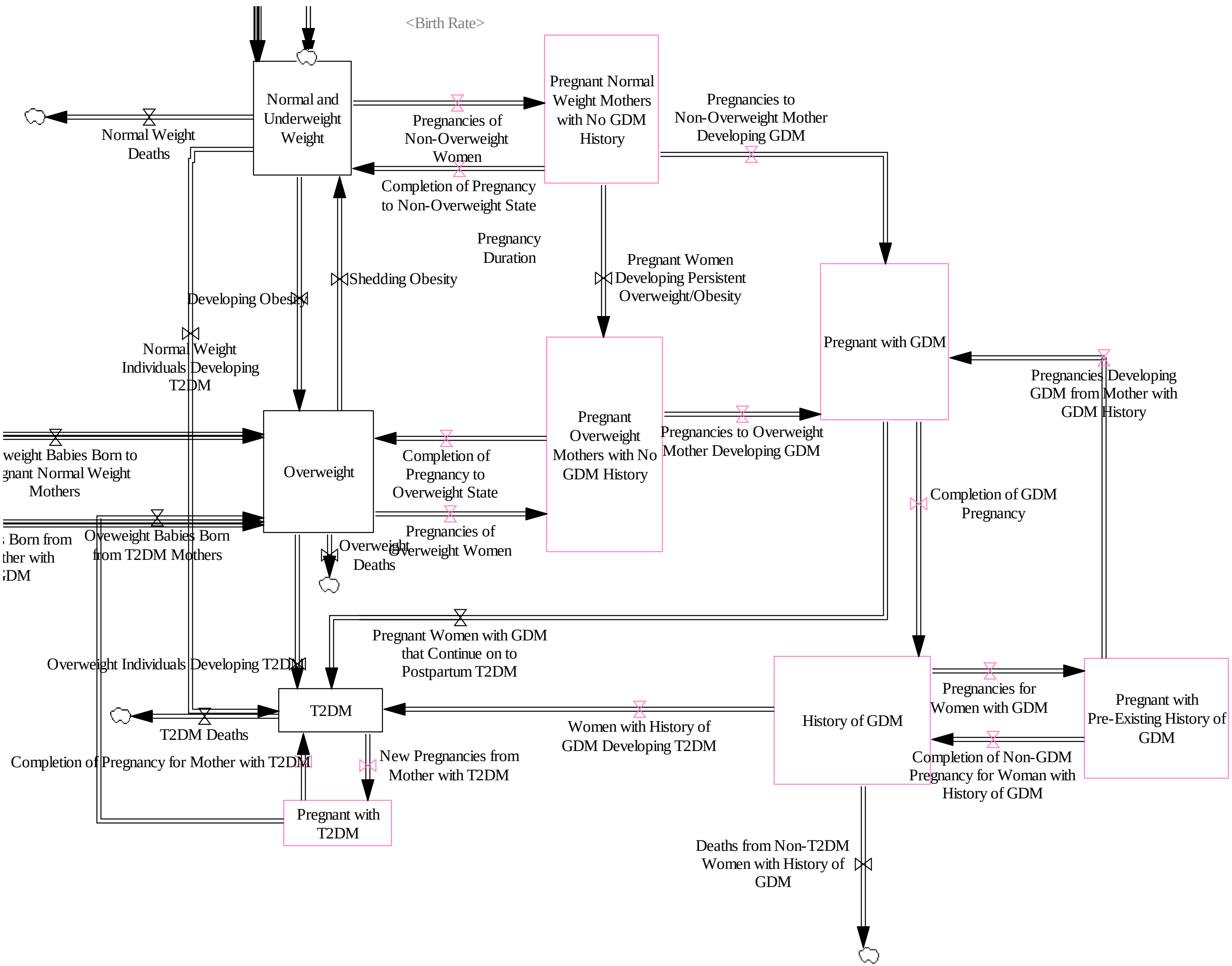
These variables are aspects of *state*.



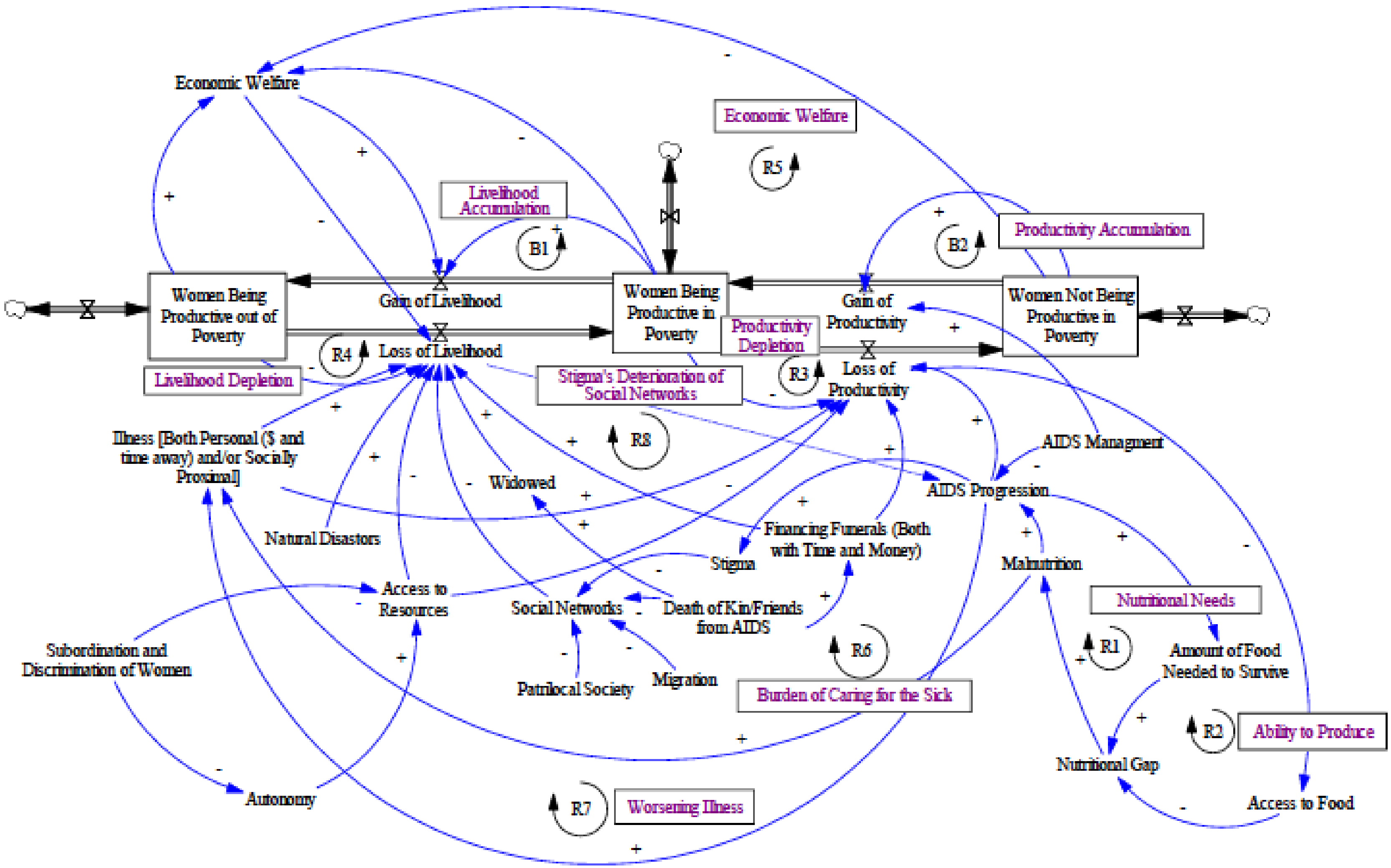
These "parameters" give static characteristics of the agent

These describe the "behaviours" – the mechanisms that will govern agent dynamics

Stock & Flow Structure

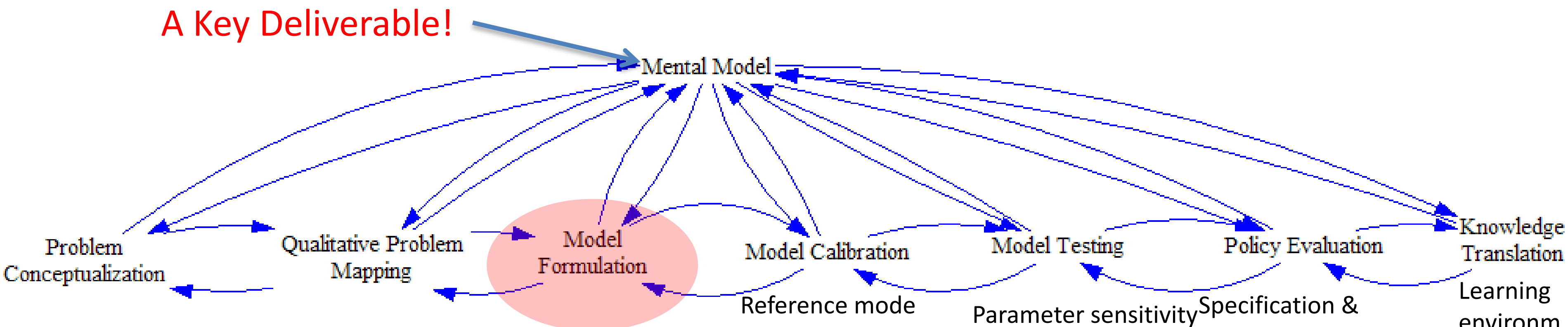


Problem Mapping: Qualitative Models (System Structure Diagram)



Headley, J., Rockweiler, H., Jogee, A. 2008. Women with HIV/AIDS in Malawi: The Impact of Antiretroviral Therapy on Economic Welfare, Proceedings of the 2008 International Conference of the System Dynamics Society, Athens, Greece, July 2008.

Modeling Process Overview



Problem Conceptualization

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Knowledge Translation

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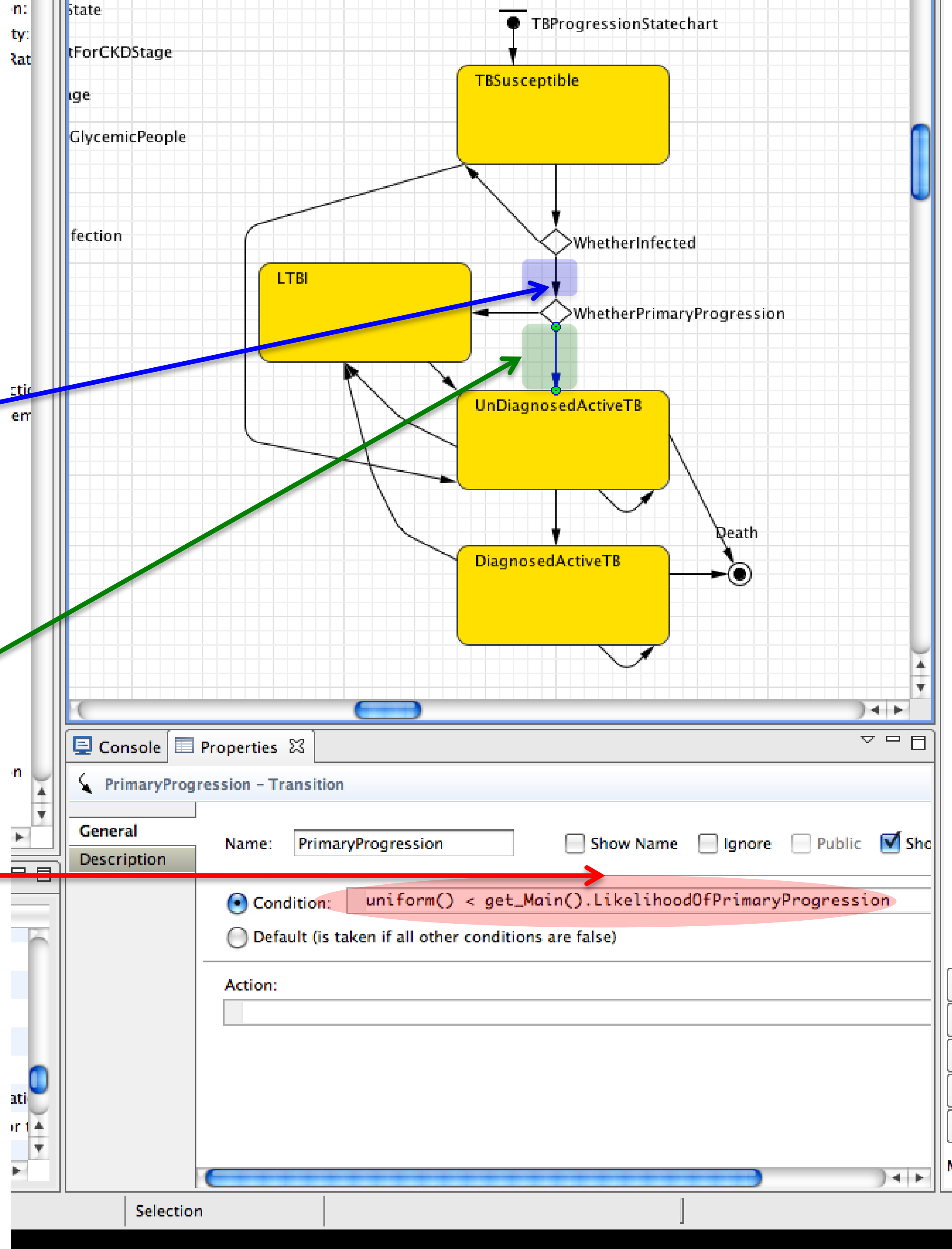
Model Formulation

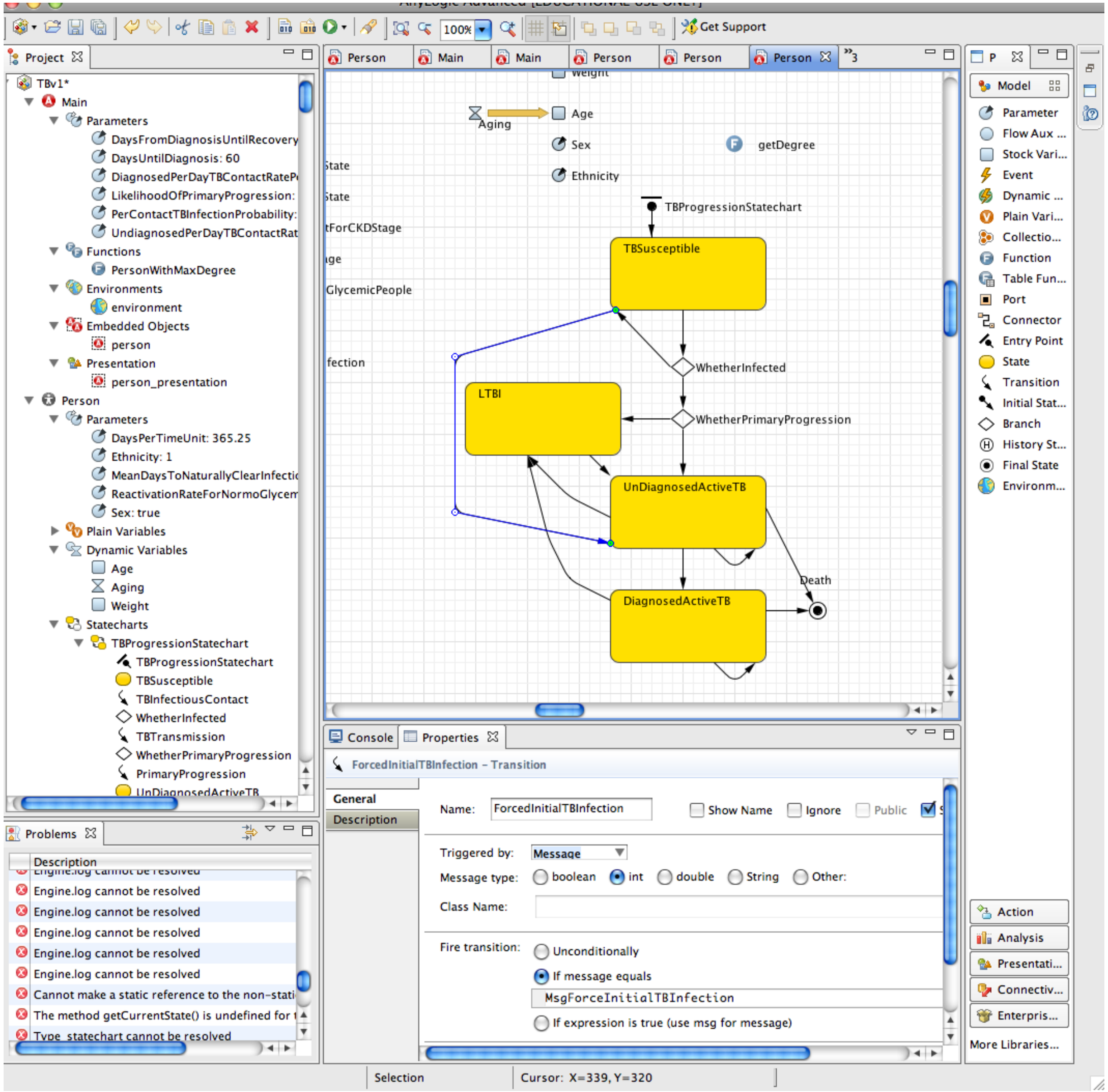
- Model formulation elaborates on problem mapping to yield a quantitative model
- Key missing ingredients
  - Specifying formulas for
    - Statechart transitions
    - Flows (in terms of other variables)
    - Intermediate/output variables
  - Parameter values

Example Conditional Transition

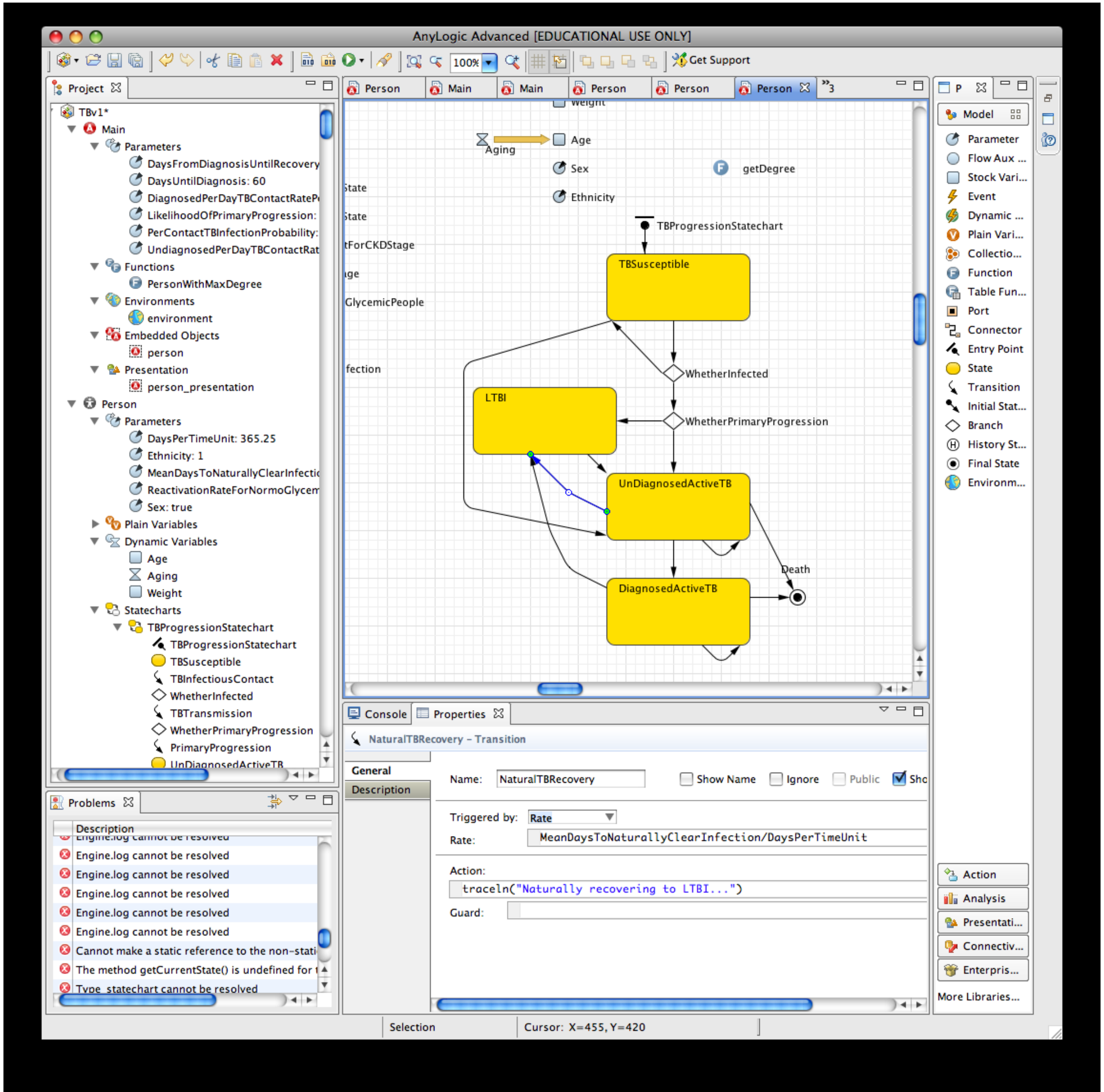
The incoming transition into "WhetherPrimaryProgression" will be routed to thisoutgoing transitionif this condition is true



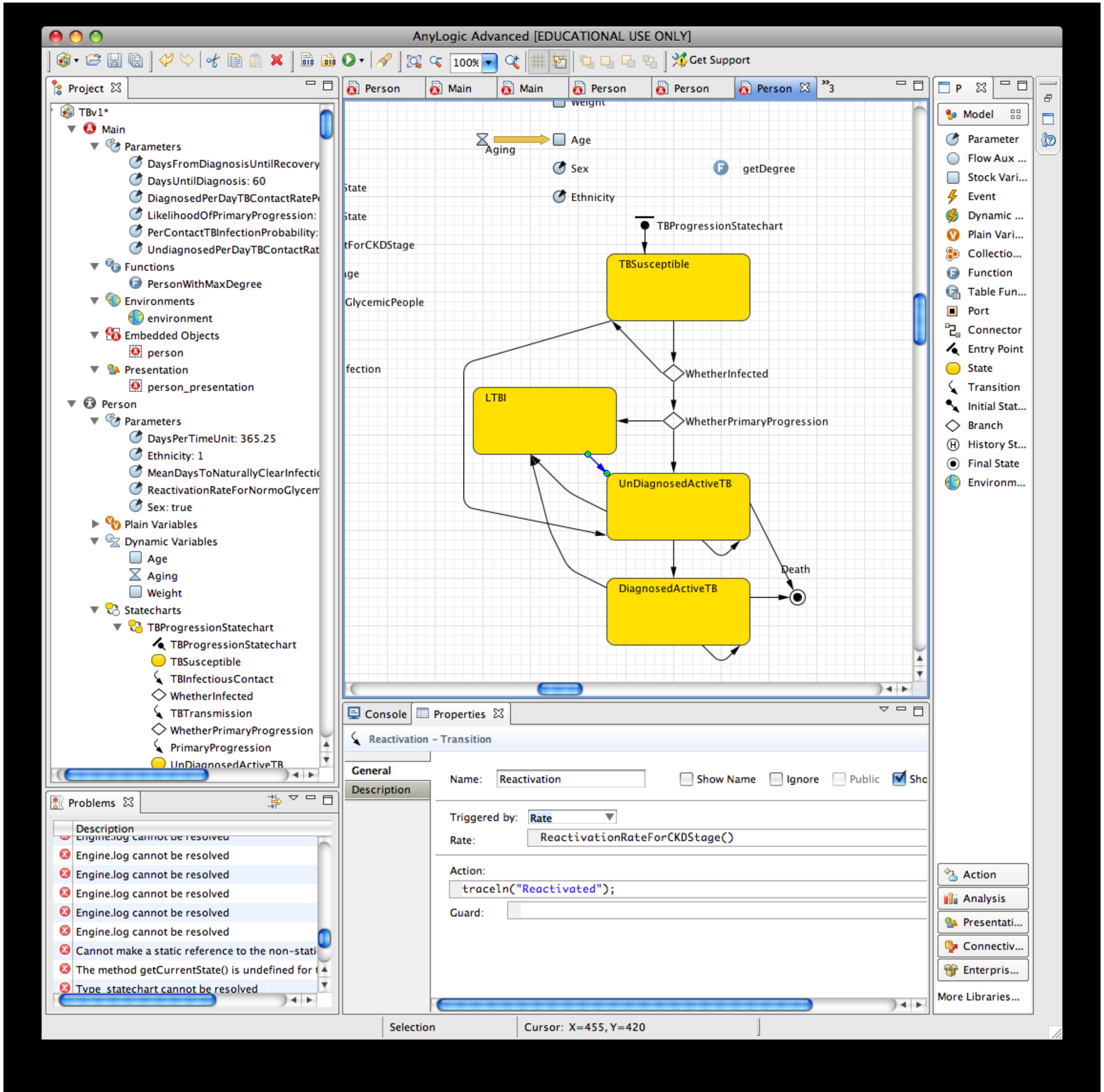
Transition Type: Message Triggered



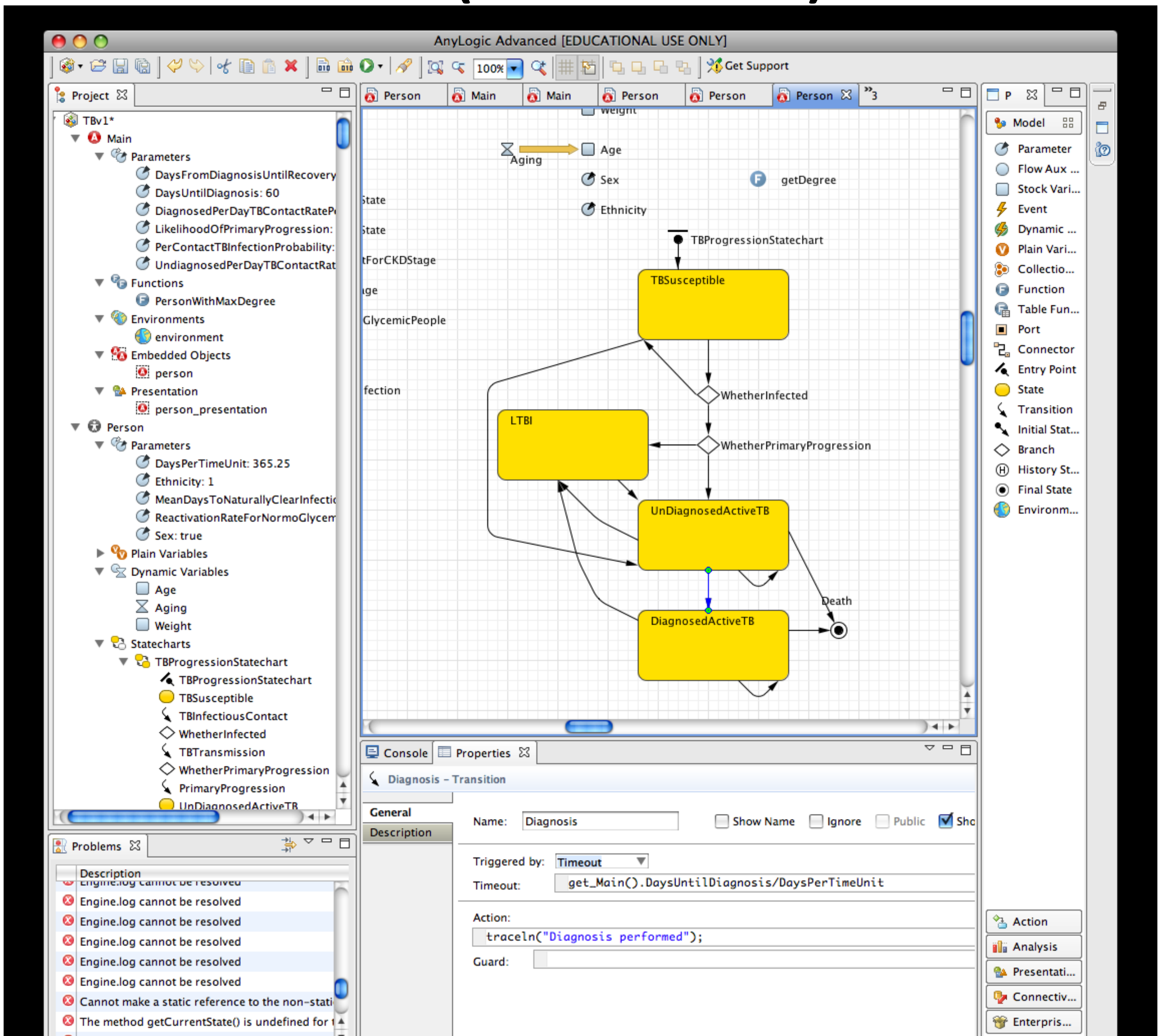
Transition Type: Fixed Rate



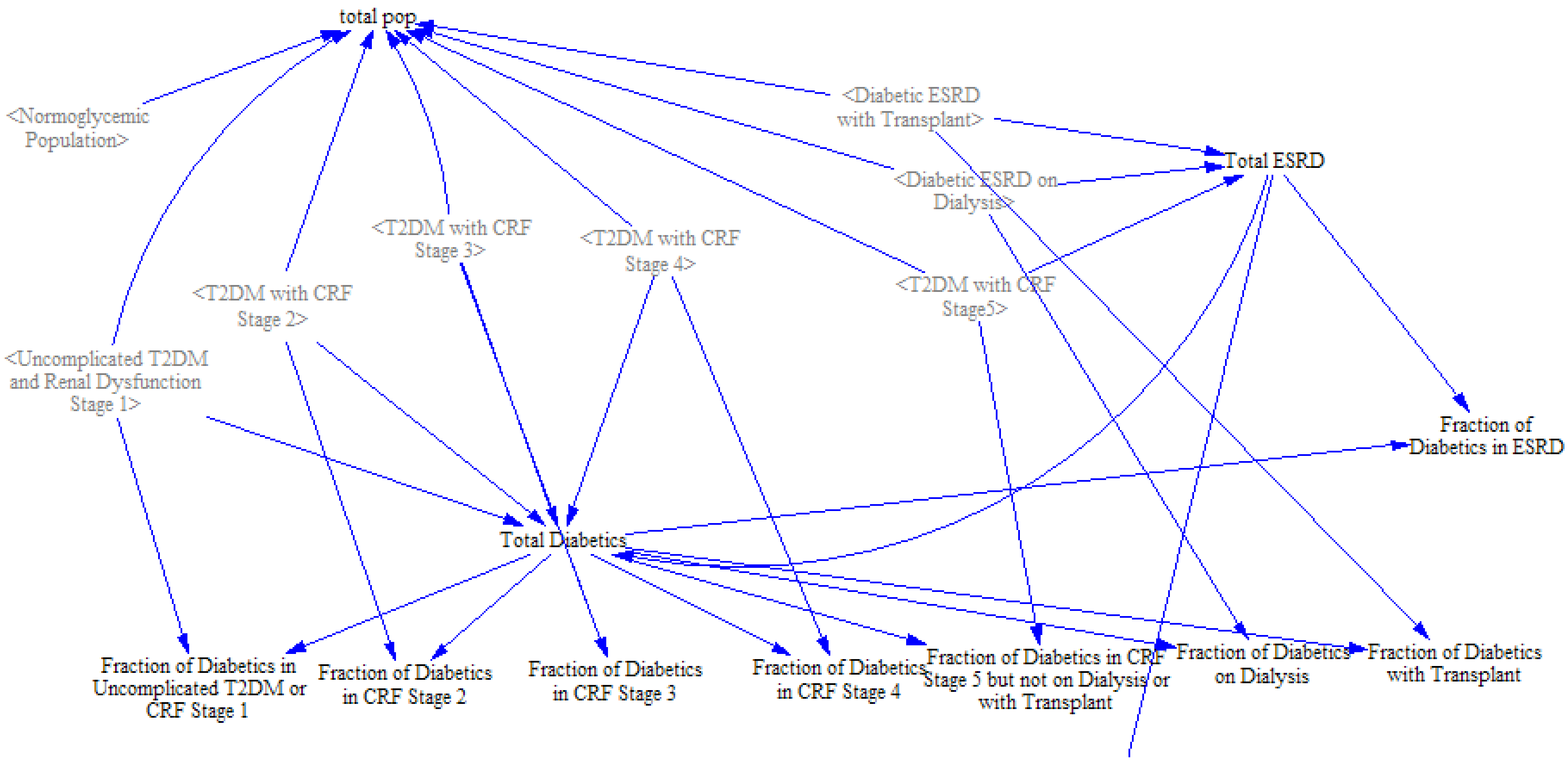
Transition Type: Variable Rate



Transition Type: Fixed Residence Time (Timeout)



Simple Intermediate Variable



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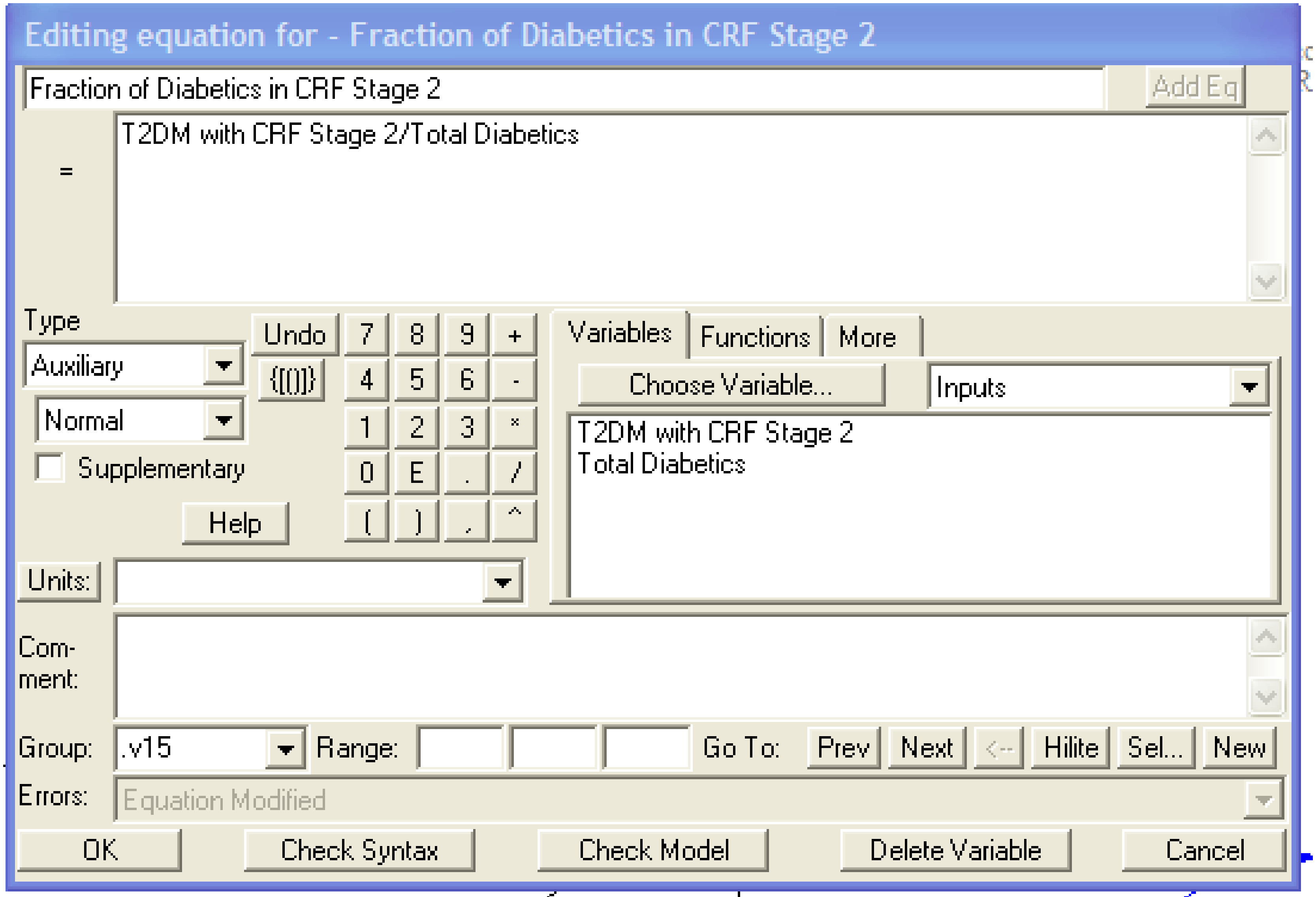
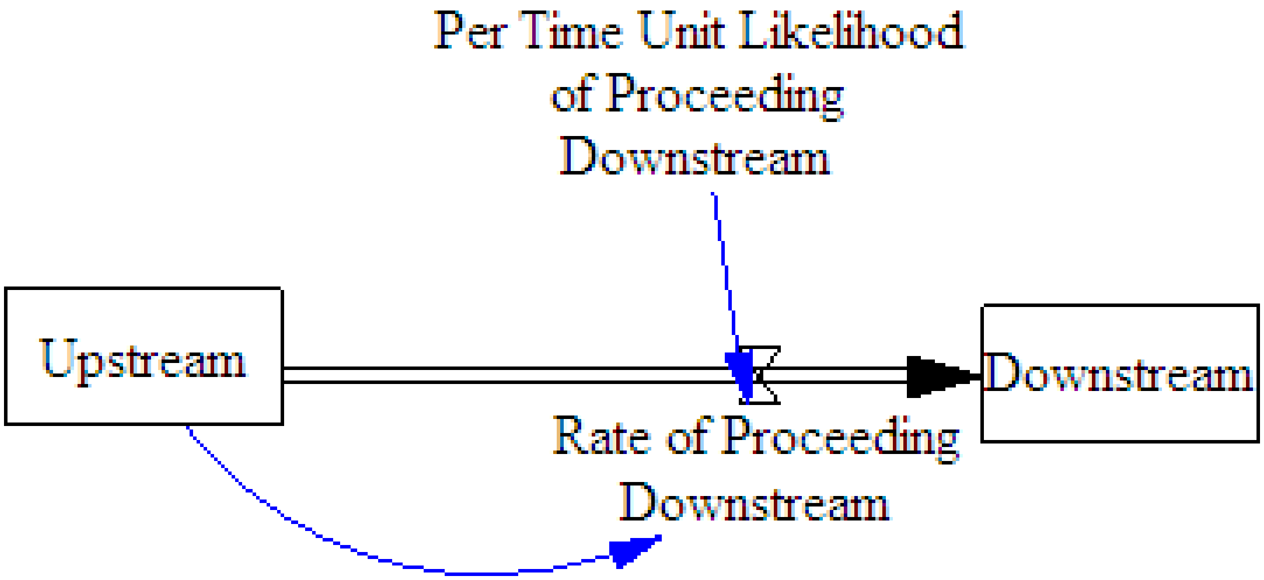
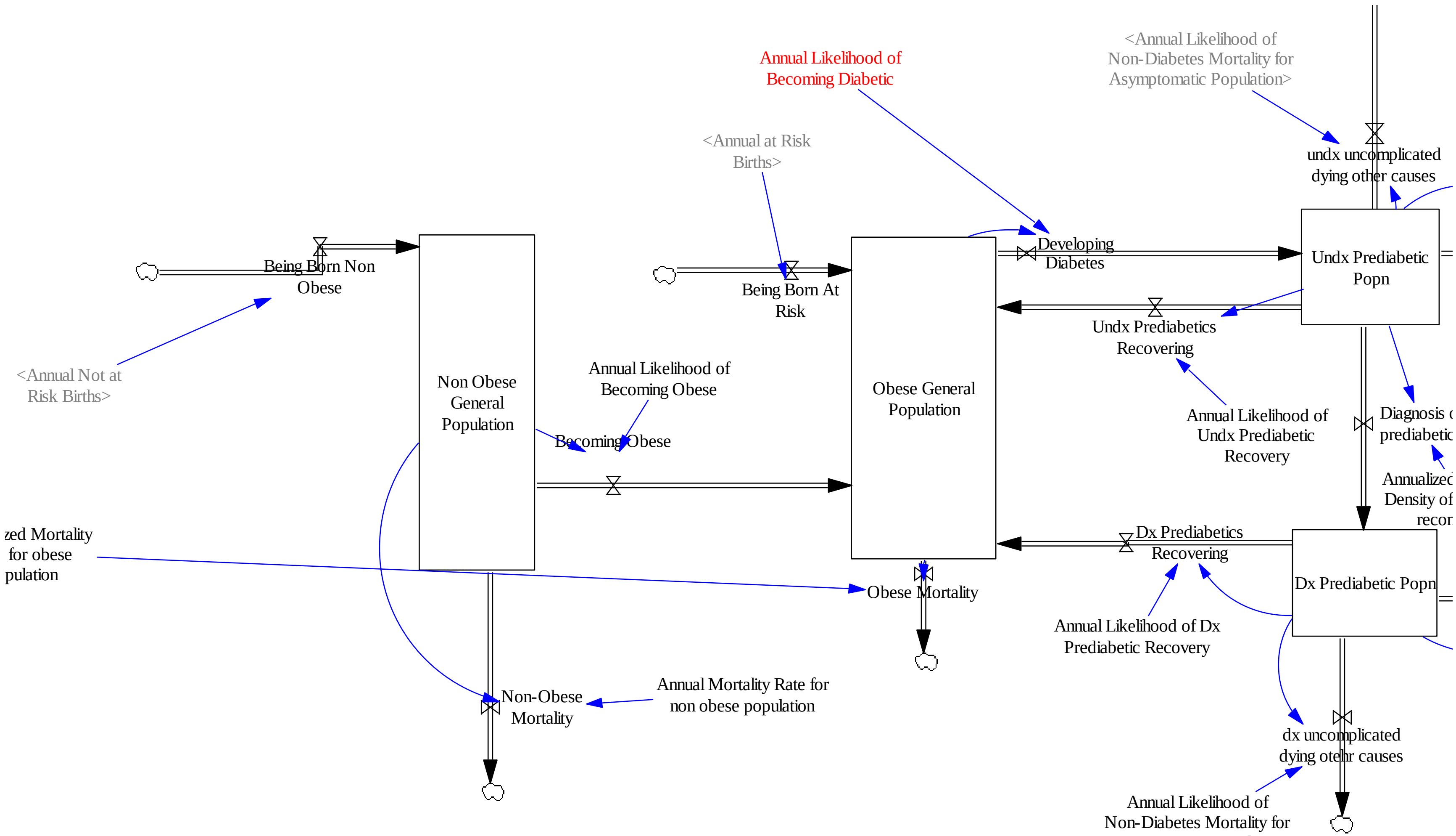


Simple Basis for Formula: 1st Order Delay



Model Stock & Flow Structure



More Sophisticated Formula: Contact Rates and Transmission Probs.

- Contacts per susceptible: c
- Fraction of contacts that are infective: Y/N
- Per-contact transmission probability: β
- “Force of infection”: Likelihood each susceptible will be infected per unit time
  - Common formulation
    - $c(Y/N)\beta$
- Flow: Total # infections per unit time
  - $X^*(\text{Force of Infection}) = X(c(Y/N)\beta)$
  - Note that this $= Y(c(X/N)\beta)$

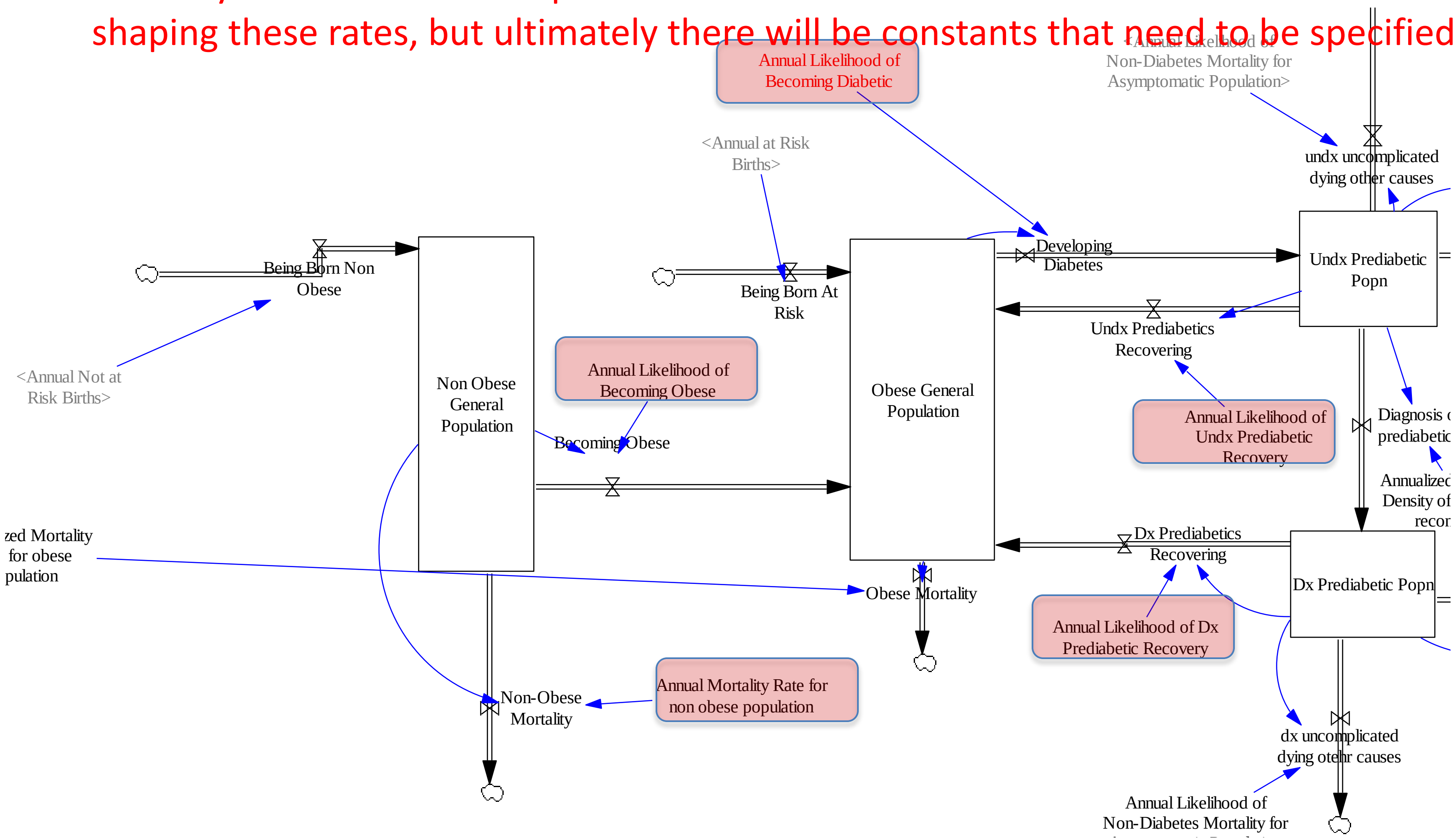
Sources for Parameter Estimates

- Surveillance data
- Controlled trials
- Outbreak data
- Clinical reports data
- Intervention outcomes studies
- Calibration to historic data
- Expert judgement
- Systematic reviews

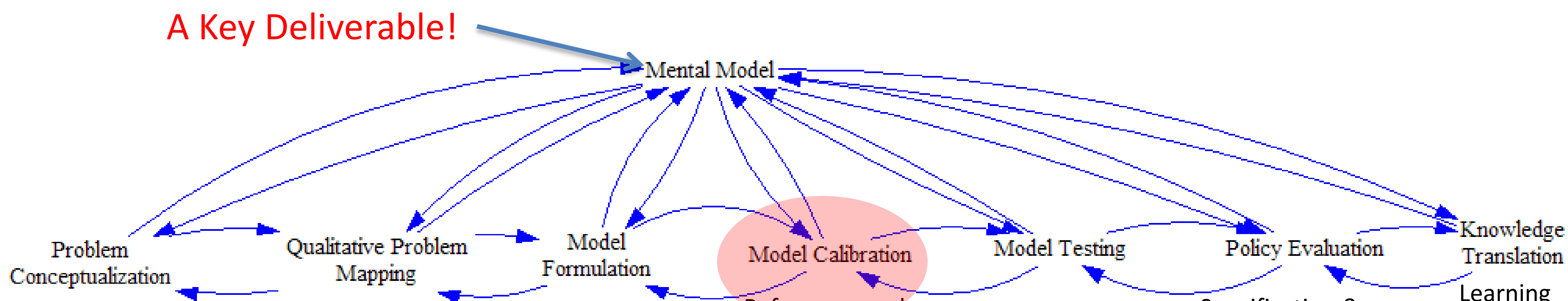
Parameter*	Description	Baseline value (units)	Reference
μ	Entry/exit of sexual activity	0.0056 (years^{-1})	Garnett and Bowden, 2000
c	Partner change rate per Susceptible	16.08 (years^{-1})	Approximated from Garnett and Bowden, 2000
β	Probability of infection per sexual contact	0.70	Garnett and Bowden, 2000
φ	Fraction of Infectives who are symptomatic	0.20	Garnett and Bowden, 2000
$1/\gamma$	Latent period	0.038 (years)	Brunham et. al., 2005
$1/\sigma$	Duration of infection	0.25 (years)	Brunham et. al., 2005
θ	Asymptomatic recovery coefficient	1.5	Garnett and Bowden, 2000
$1/\pi$	Duration of naturally-acquired immunity	1 (year)	Approximated from Brunham et. al., 2005

Introduction of Parameter Estimates

Some dynamics models will provide much more detail on networks of factors shaping these rates, but ultimately there will be constants that need to be specified



Modeling Process Overview



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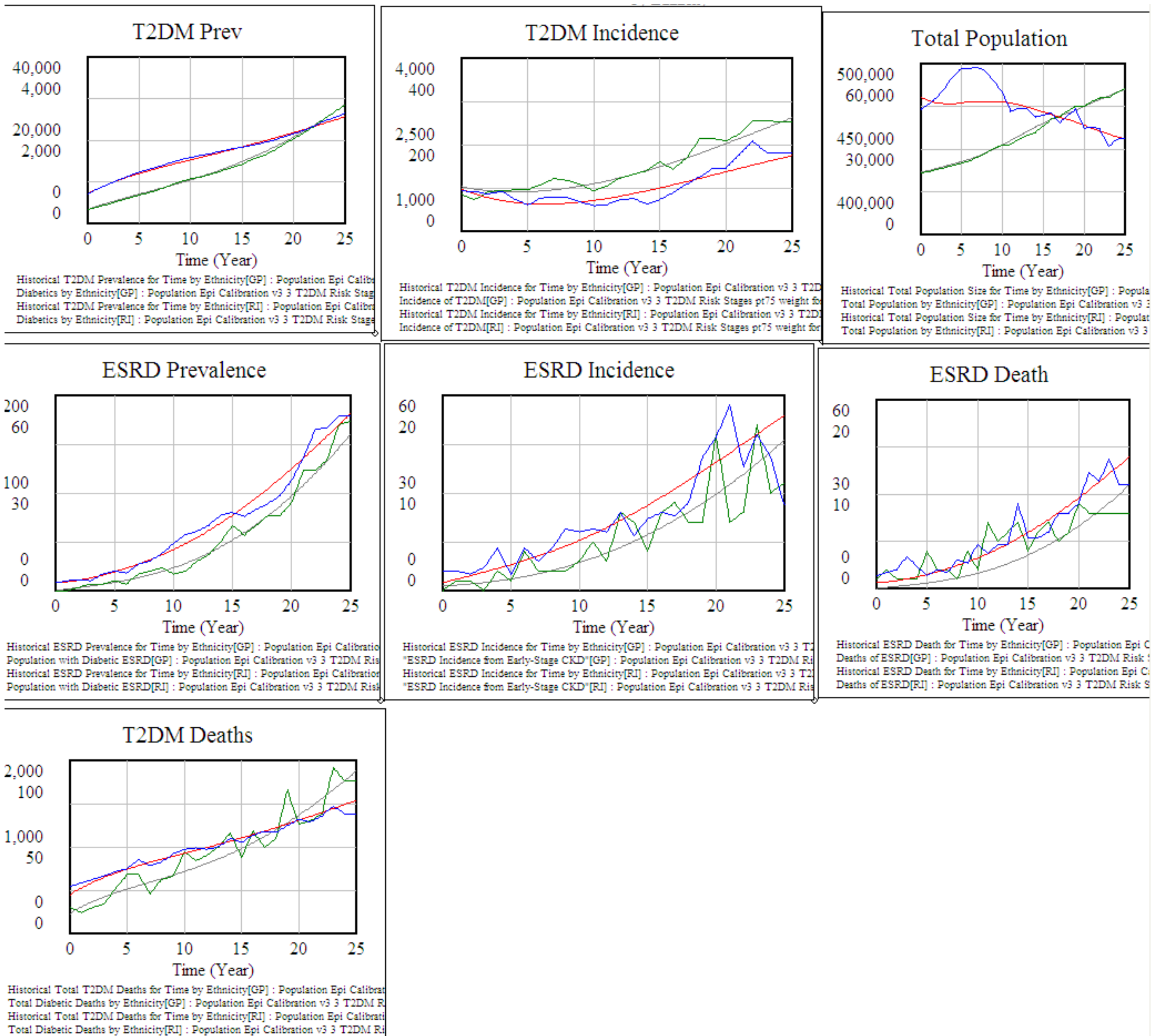
Calibration

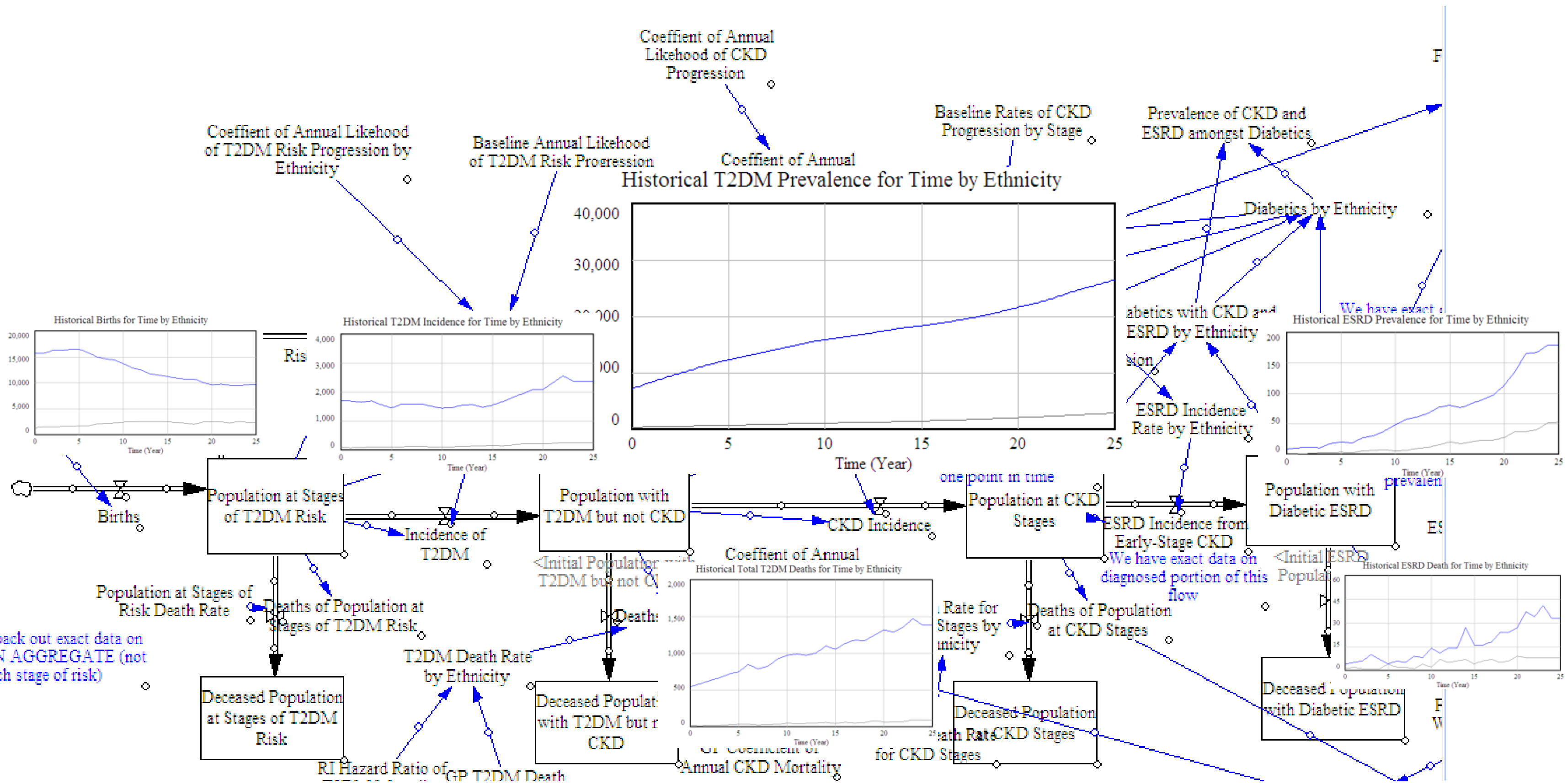
- Often we don’t have reliable information on *some* parameters
  - Some parameters may not even be observable!
- Some parameters may implicitly capture a large set of factors not explicitly represented in model
- Often we will calibrate less well known parameters to match observed data
  - “Analytic triangulation”: Often try to match against *many* time series or pieces of data at once
- Sometimes we learn from this that our model structure just can’t produce the patterns!

Single Model Matches Many Data Sources

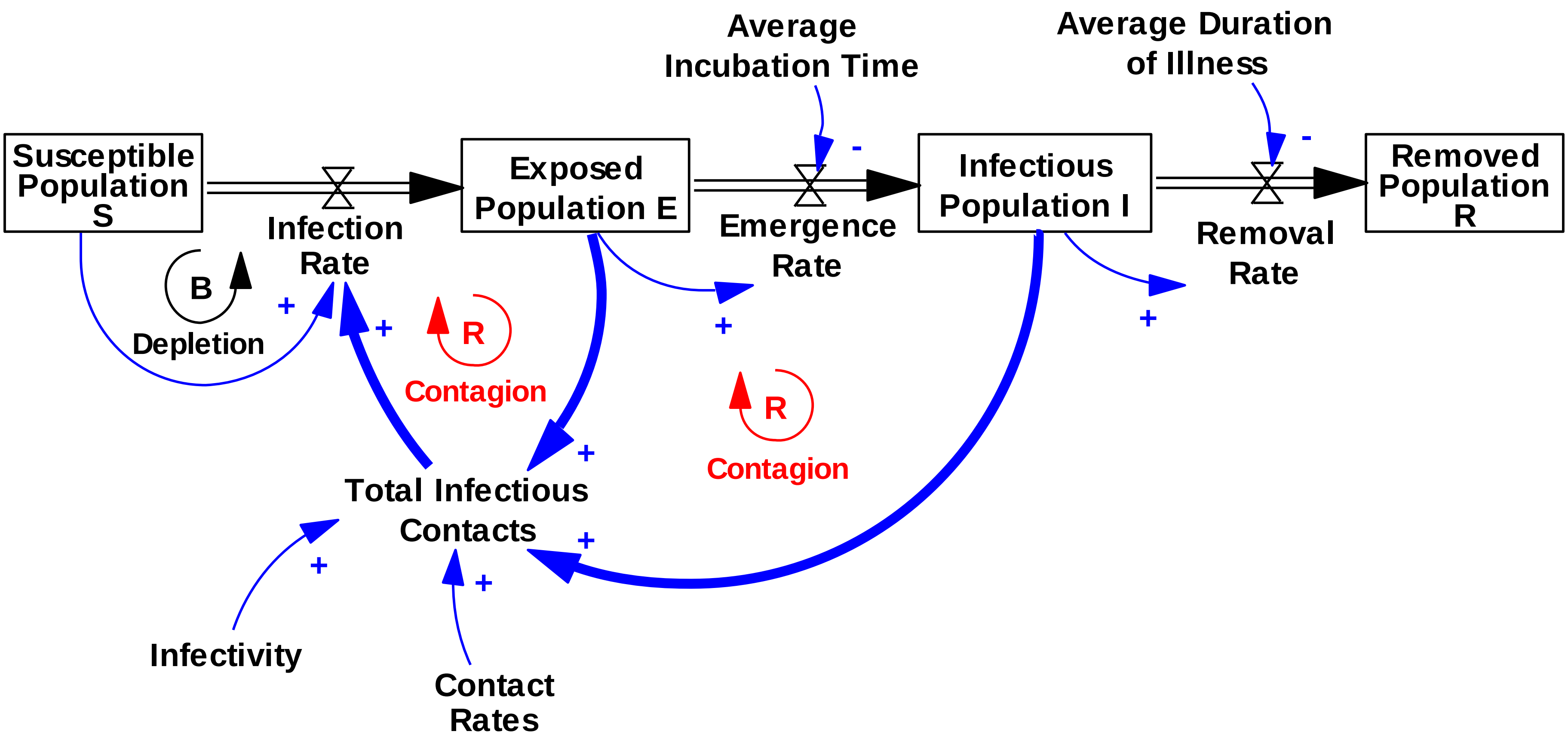


one of

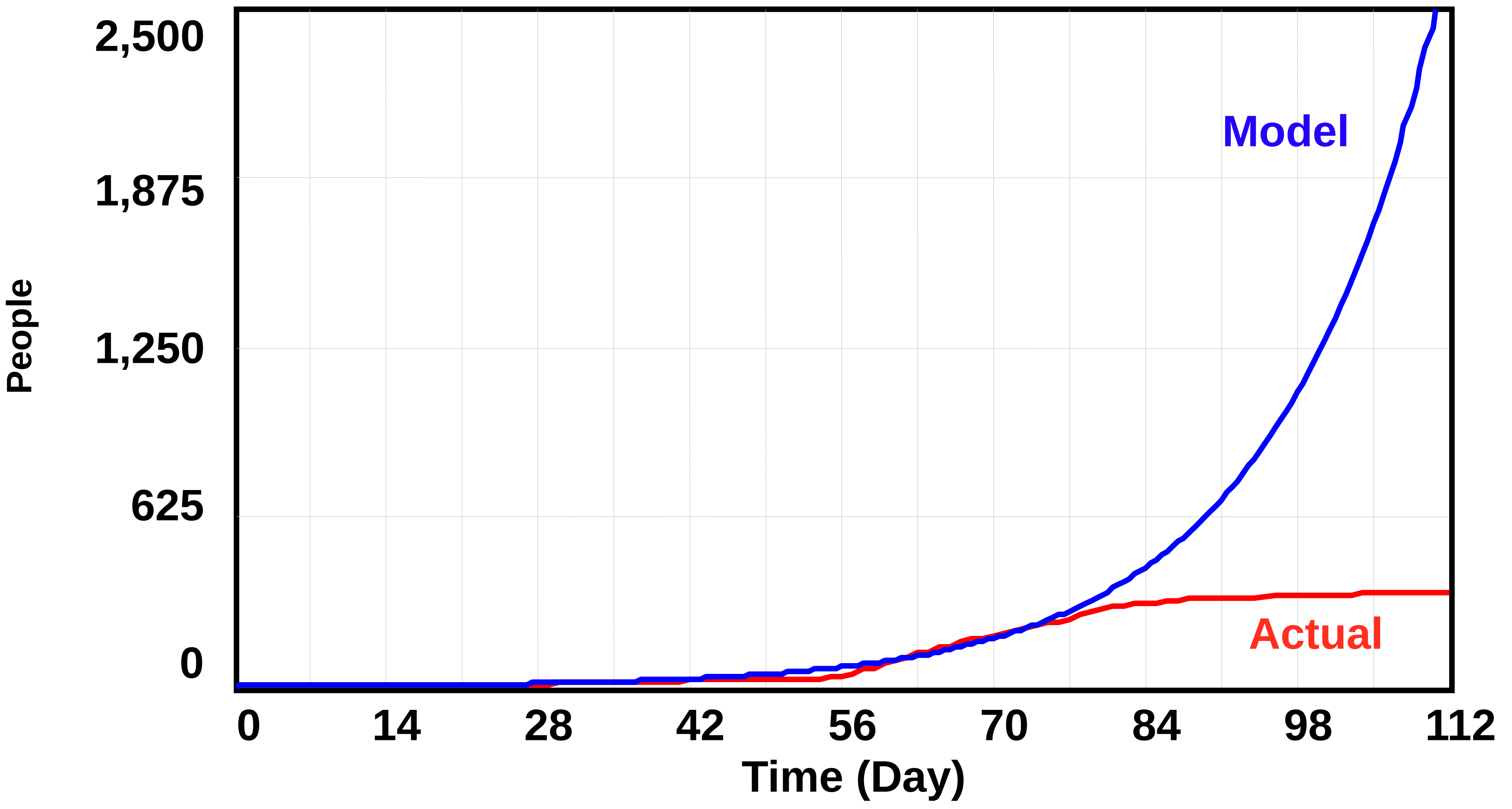
The Pieces of the Elephant
Example Model of Underlying Process & Time Series It Must Match



Example: Iteration & Calibration

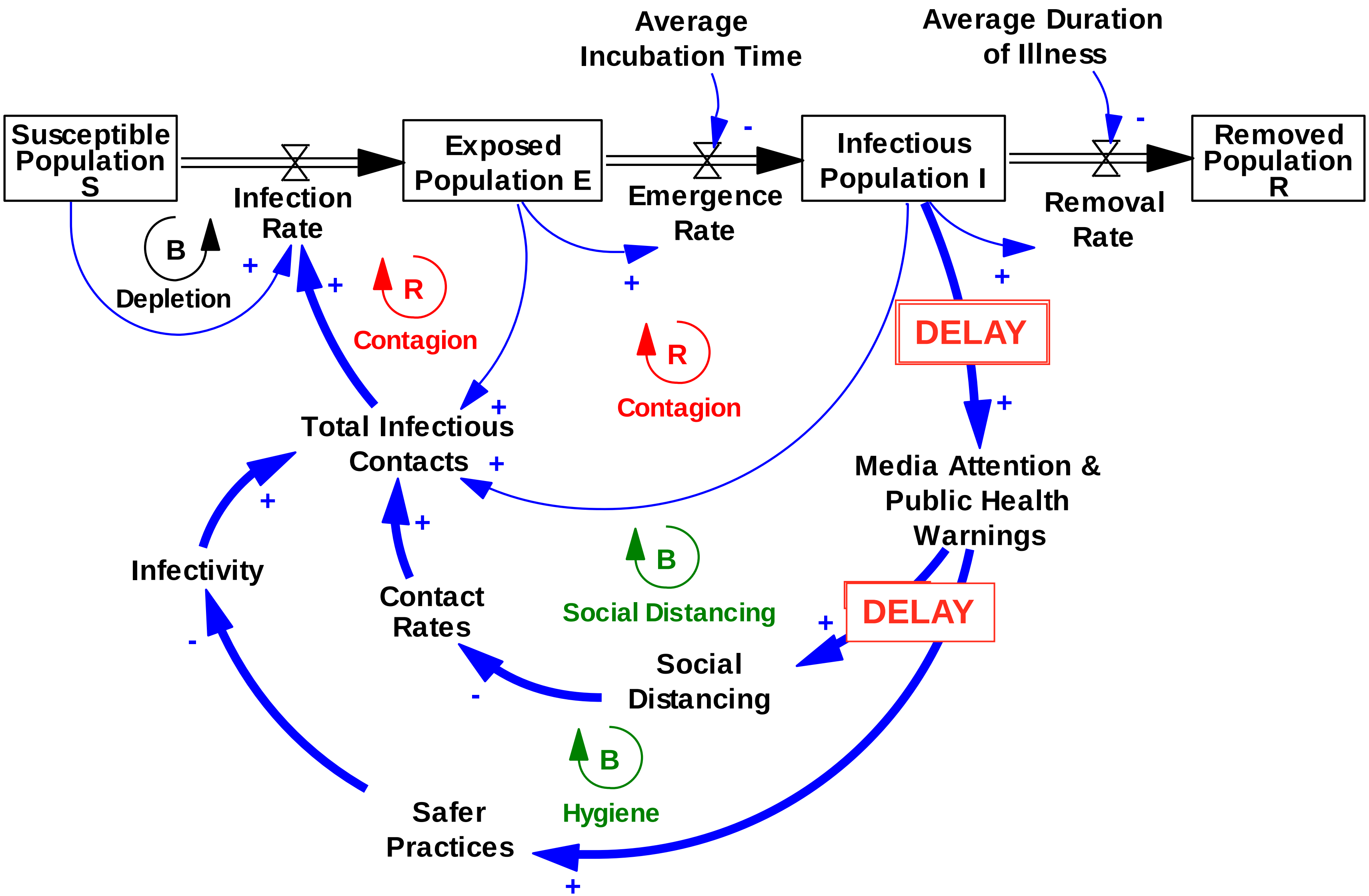


From Sterman

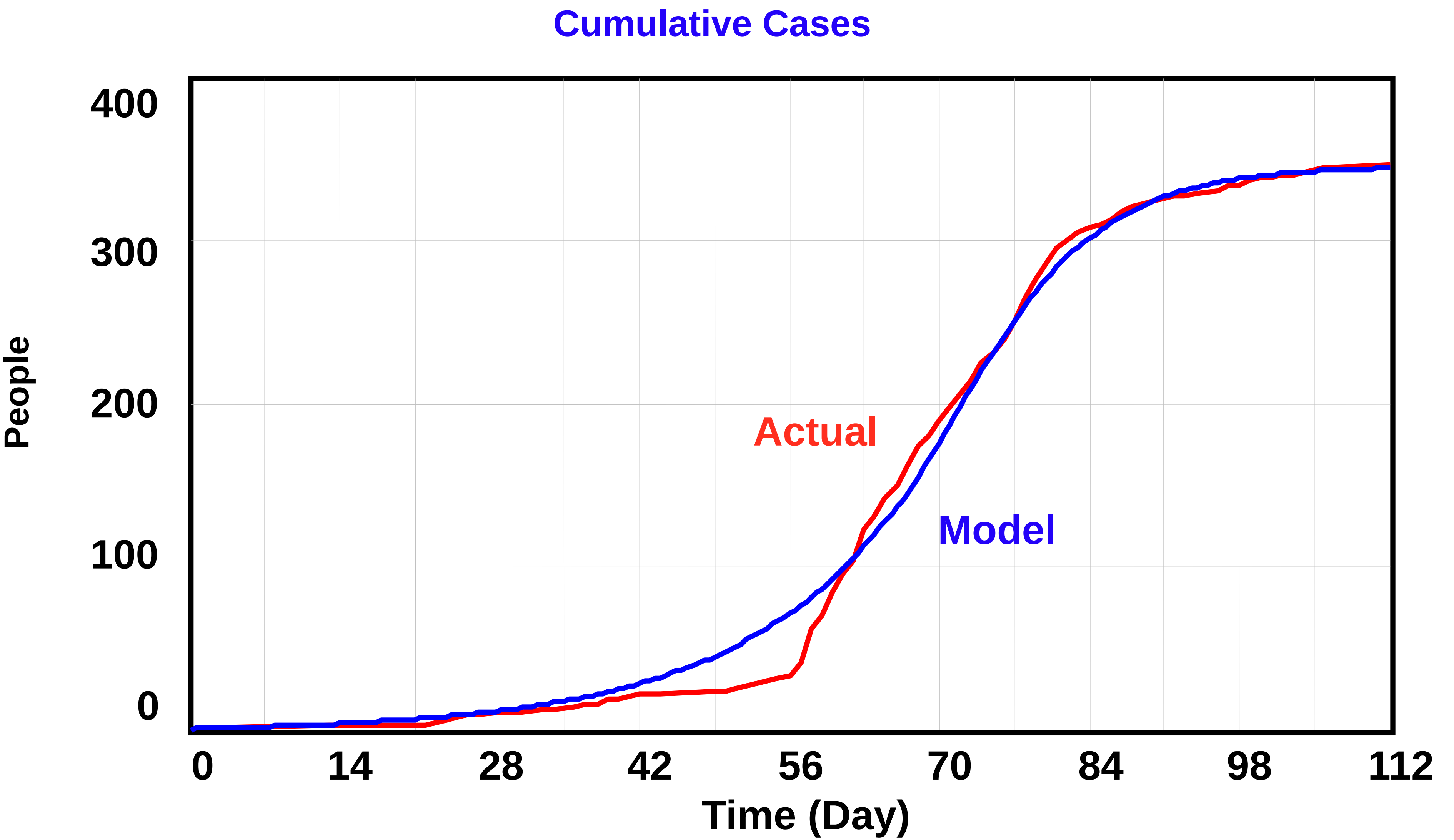


From Sterman

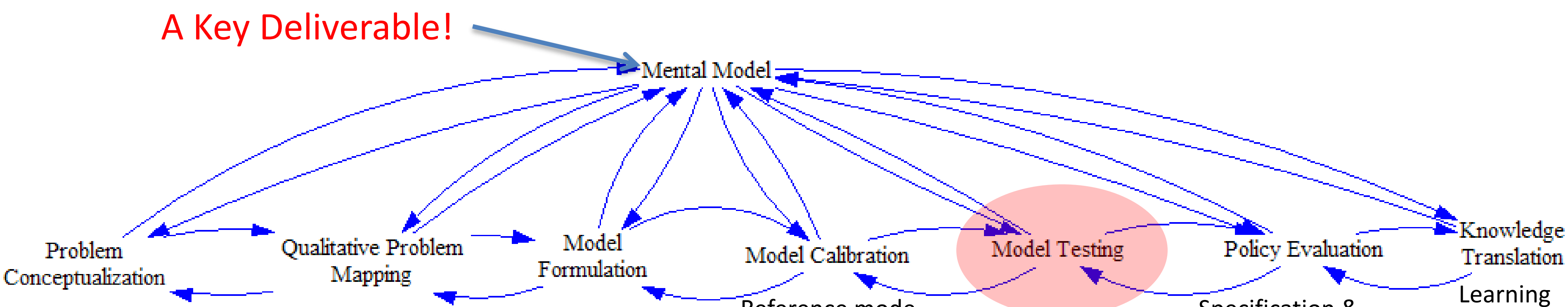
Expanding the Boundary: Behavioral Feedbacks



From Sterman


Cumulative Cases
People
400
300
200
100
0
Actual
Model
0
14
28
42
56
70
84
98
112
Time (Day)

Modeling Process Overview



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Units & Dimensions

- Distance
  - Dimension: Length
  - Units: Meters/Fathoms/Li/Parsecs
- Frequency (Growth Rate, etc.)
  - Dimension:1/Time
  - Units: 1/Year, 1/sec, etc.
- Fractions
  - Dimension: “Dimensionless” (“Unit”, 1)
  - Units: 1

Dimensional Analysis

- DA exploits structure of dimensional quantities to facilitate insight into the external world
- Uses
  - Cross-checking dimensional homogeneity of model
  - Deducing form of conjectured relationship
    (including showing independence of particular factors)
  - Sanity check on validation of closed-form model analysis
  - Checks on simulation results
  - Derivation of scaling laws

  * Construction of scale models
  - Reducing dimensionality of model calibration, parameter estimation

Sensitivity Analyses

- Same relative or absolute uncertainty in different parameters may have hugely different effect on outcomes or decisions
- Help identify parameters that strongly affect
  - Key model results
  - Choice between policies
- We place more emphasis in parameter estimation into parameters exhibiting high sensitivity

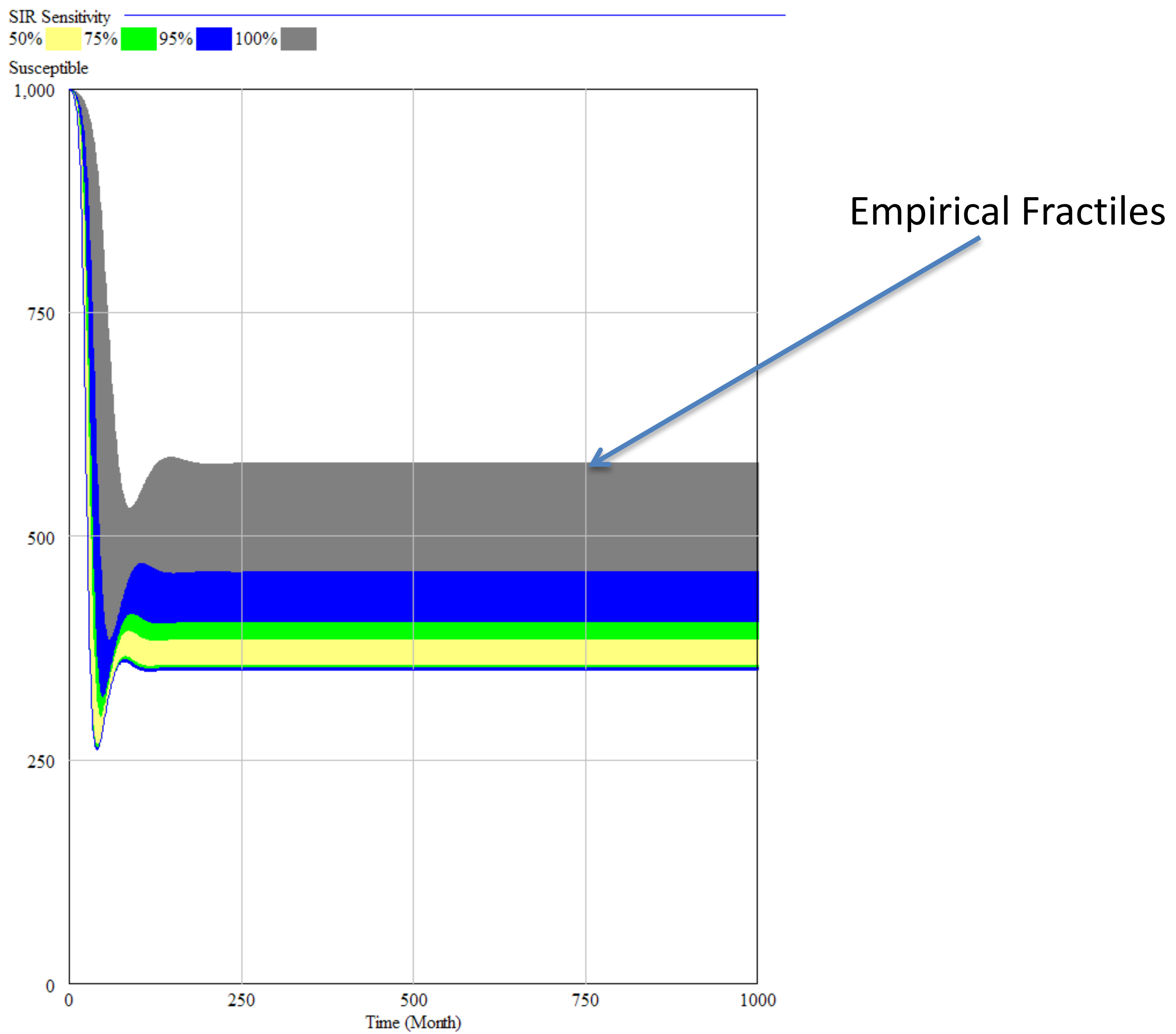
Sensitivity in Initial Value

- Frequently we don’t know the exact state of the system at a certain point in time
- A very useful type of sensitivity analysis is to vary the initial value of model stocks
- In Vensim, this can be accomplished by
  - Indicating a parameter name within the “initial value” area for a stock
  - Varying the parameter value

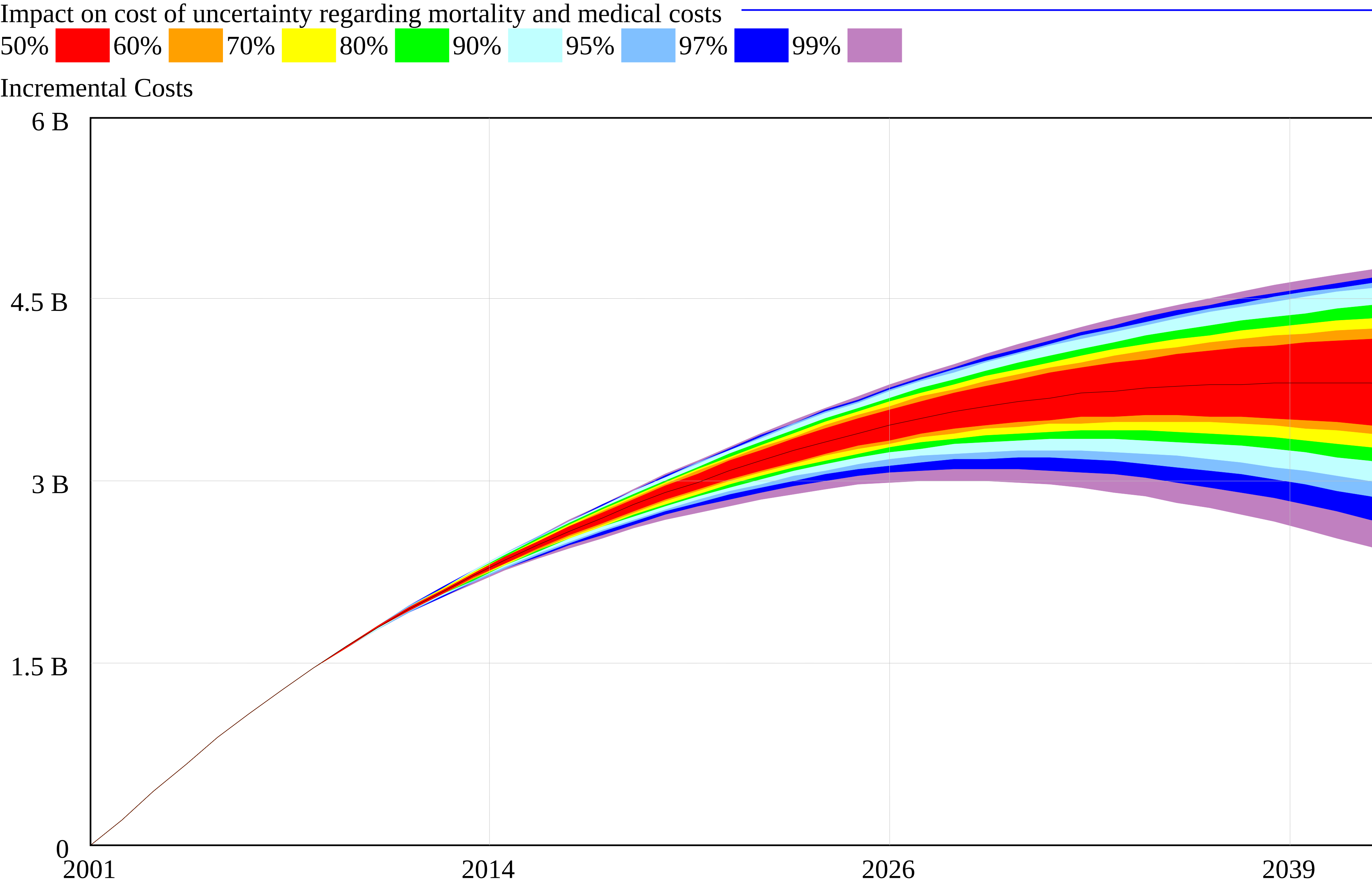
Imposing a Probability Distribution Monte Carlo Analysis

- We feed in probability distributions to reflect our uncertainty about one or more parameters
- The model is run many, many times (realizations)
  - For each realization, the model uses a different draw from those probability distribution
- What emerges is resulting probability distribution for model outputs

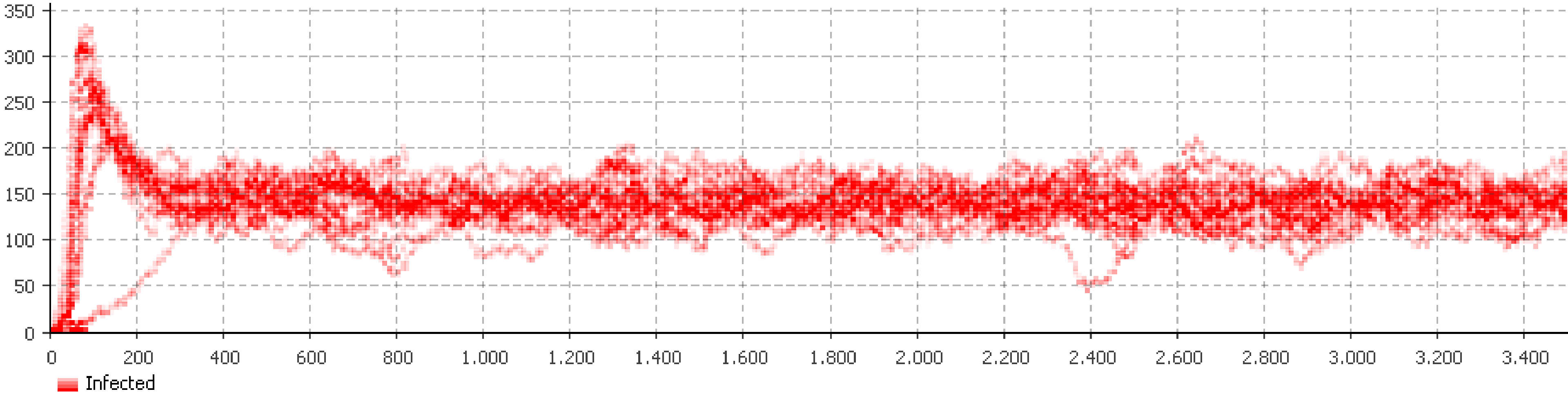
Example Resulting Distribution



Static Uncertainty



Dynamic Uncertainty: Stochastic Processes



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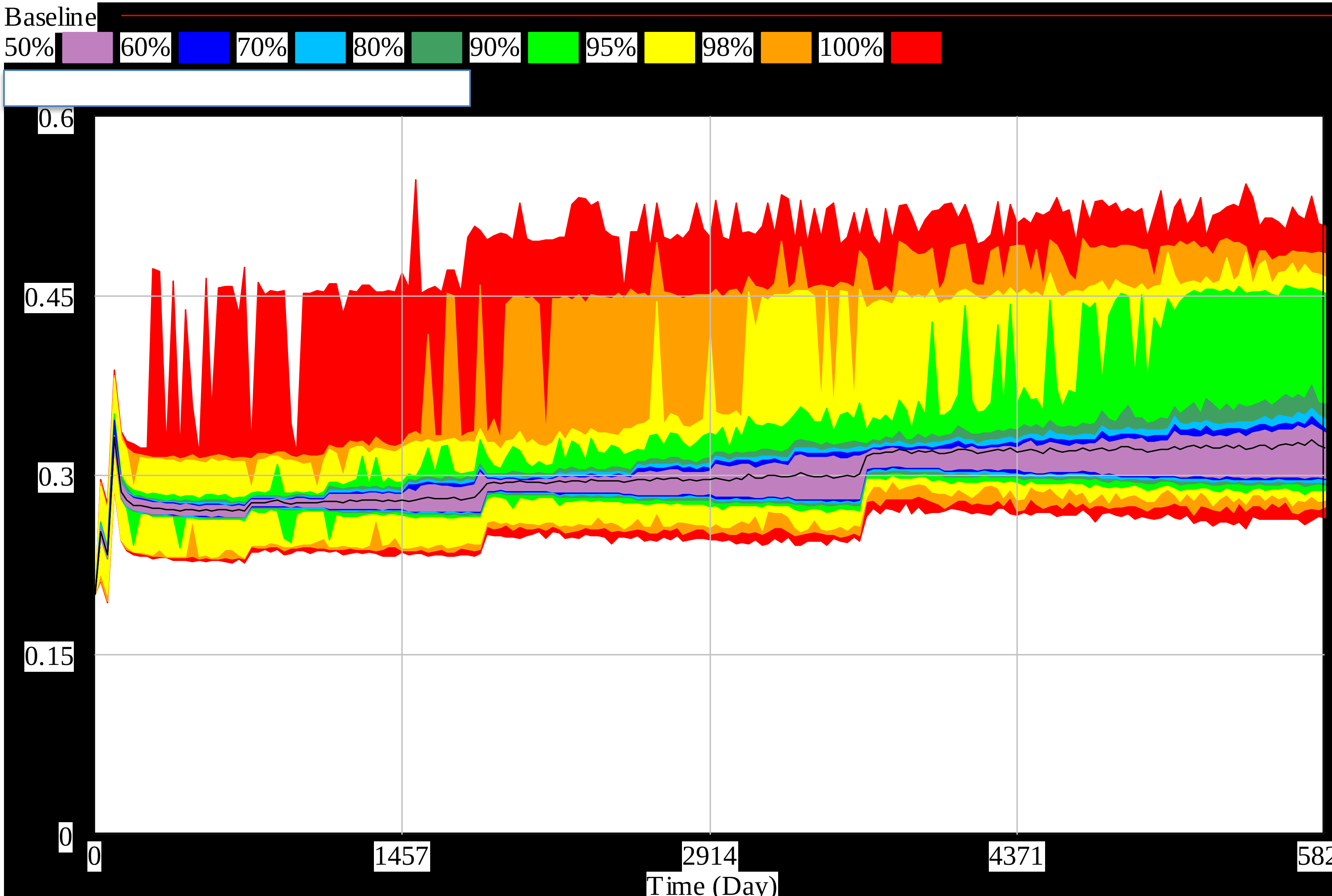


Mathematical Analysis of Models

System Linearization (Jacobian)

$$\begin{bmatrix} -\beta\, Infectives - \delta & -\beta\, S - \delta \\ \beta\, Infectives & \beta\, S - \dfrac{1}{\mu + \dfrac{\tau\, Infectives}{h}} + \dfrac{Infectives\, \tau}{\left(\mu + \dfrac{\tau\, Infectives}{h}\right)^2 h} \end{bmatrix}$$

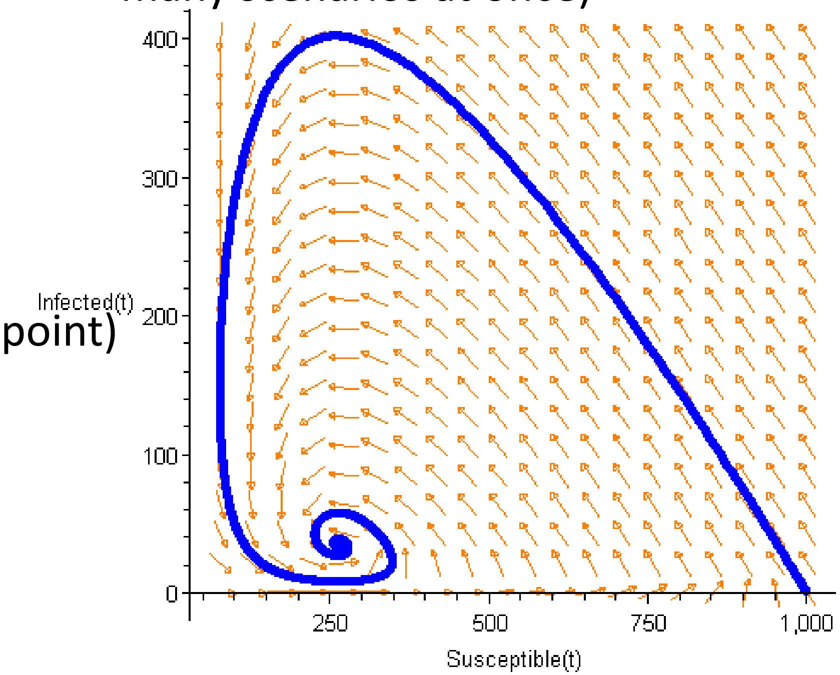
Fixed-Point Criteria

$$\dot{S} = -c\left(\frac{I}{N}\right)\hat{\beta}S + R\delta = 0$$

$$\dot{I} = c\left(\frac{I}{N}\right)\hat{\beta}S - \frac{I}{\mu + \tau\dfrac{I}{h}} = 0$$

$$\dot{R} = \frac{I}{\mu + \tau\dfrac{I}{h}} - R\delta = 0$$

State space diagram (reasoning about many scenarios at once)



Eigenvalues (e.g. for stability analysis around fixed-point)

$$\frac{1}{2}\beta\, S - \frac{1}{2}\frac{1}{\mu + \frac{\tau\, Infectives}{h}} + \frac{1}{2}\frac{Infectives\, \tau}{\left(\mu + \frac{\tau\, Infectives}{h}\right)^2 h} - \frac{1}{2}\beta\, Infectives - \frac{1}{2}\delta$$
$$+ \frac{1}{2}\left(\left(\beta\, S - \frac{1}{\mu + \frac{\tau\, Infectives}{h}} + \frac{Infectives\, \tau}{\left(\mu + \frac{\tau\, Infectives}{h}\right)^2 h}\right)^2 - 2\left(\beta\, S - \frac{1}{\mu + \frac{\tau\, Infectives}{h}}\right.\right.$$
$$\left.\left. + \frac{Infectives\, \tau}{\left(\mu + \frac{\tau\, Infectives}{h}\right)^2 h}\right)\left(-\beta\, Infectives - \delta\right) + \left(-\beta\, Infectives - \delta\right)^2 + 4\,\beta\, Infectives\left(-\beta\, S - \delta\right)\right)^{\frac{1}{2}}$$

Applied Math & Dynamic Modeling

- Although you may not use it, the dynamic modeling presented rests on the tremendous deep & rich foundation of applied mathematics
  - Linear algebra
  - Calculus (Differentia/Integral, Uni& Multivariate)
  - Differential equations
  - Numerical analysis (including numerical integration, parameter estimation)
  - Control theory
- For the mathematically inclined, the tools of these areas of applied math are available

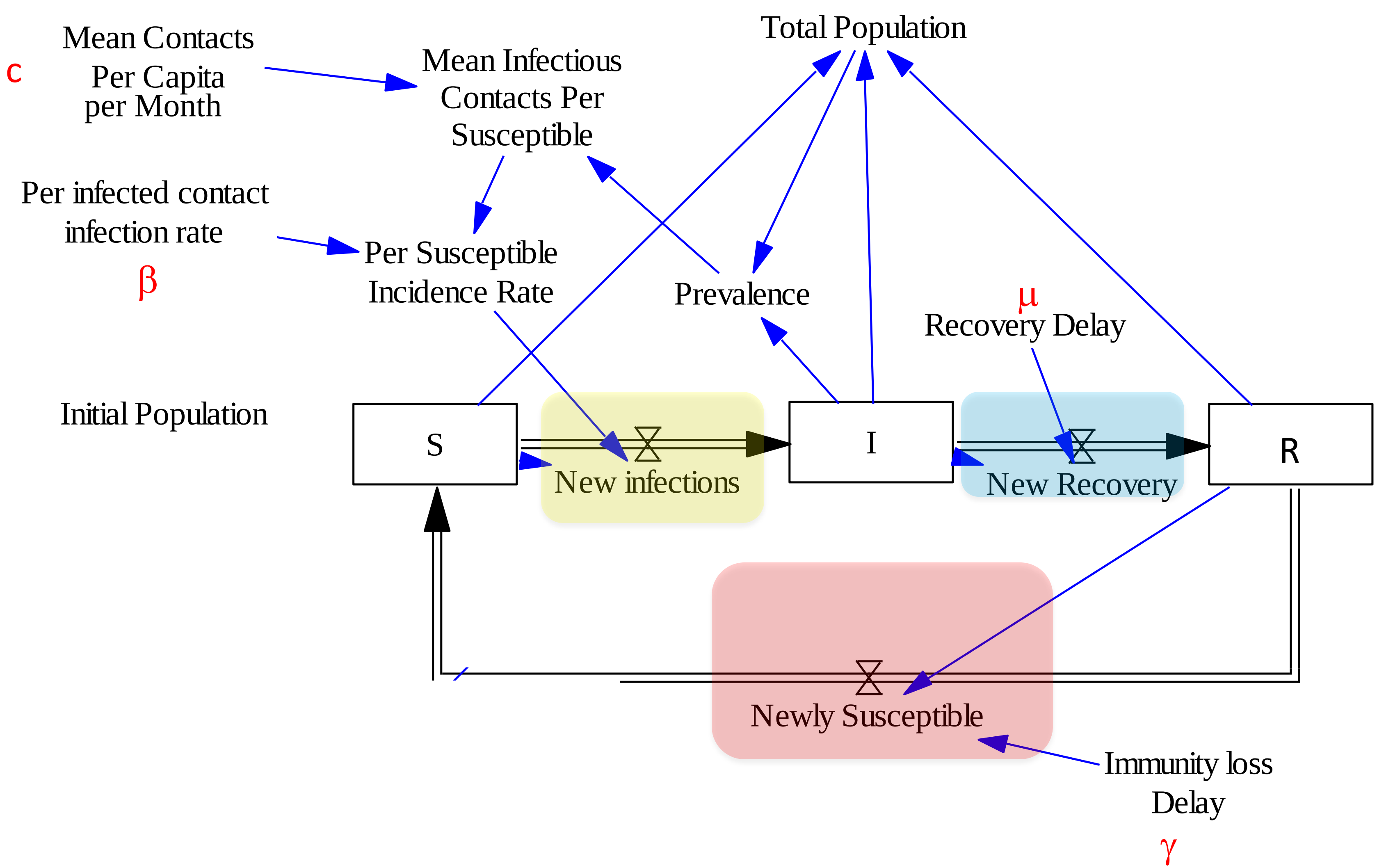
Comments on Mathematics & Dynamic Modeling

- Many accomplished & well-published dynamic modelers have limited mathematical background
  - Can investigate pressing & important issues
  - Software tools are making this easier over time
- Can gain extra insight/flexibility if willing to push to learn some of the associated mathematics
- Achieving highest skill levels in dynamic modeling do require mathematical facility and sophistication
  - To do sophisticated work, often those lacking this background or inclination collaborate with someone with background

Examples of Mathematical Insights from System Dynamics Models

- Identification of long-term behavior
  - Eventual outcome(s)
  - The impact of parameters on outcomes
  - The robustness of these outcomes to disturbance
- Insight into key causal linkages driving the system at each point in time
- Identification of high leverage parameters (interventions)
- Explanation for elements of observed behavior

Example: Simple SITS Model



Associated System of State Equations

$$\dot{S} = -c\left(\frac{I}{S+I+R}\right)\beta S + \frac{R}{\gamma}$$

These represent the same infection flow (flowing out of S, and into I)

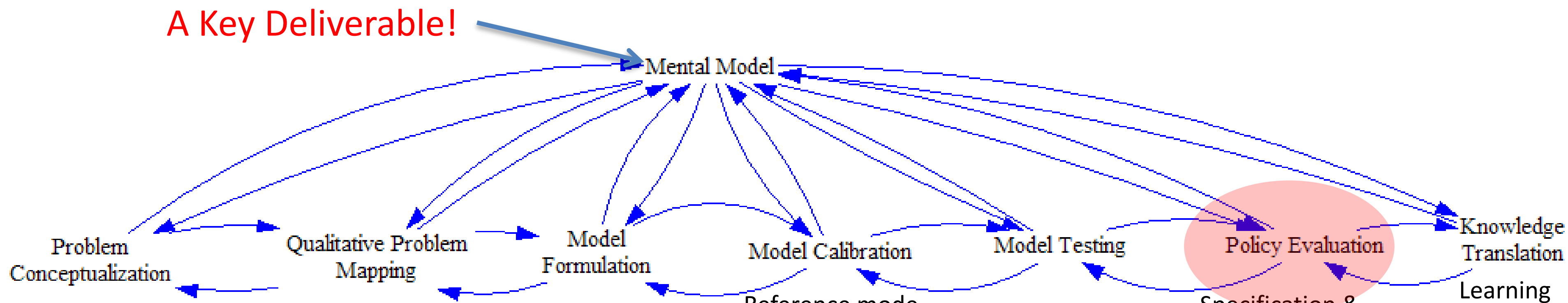
$$\dot{I} = c\left(\frac{I}{S+I+R}\right)\beta S - \frac{I}{\mu}$$

These represent the same recovery flow (flowing out of I, and into R)

$$\dot{R} = \frac{I}{\mu} - \frac{R}{\gamma}$$

These represent the same loss-of-immunity flow (flowing out of R (hence the minus sign), flowing into S)

Modeling Process Overview



Model scope/boundary selection.

Model time horizon Identification of

Key variables

Reference modes for explanation

Causal loop diagrams

State charts

System Structure diagrams

Multi-agent interaction diagrams

Multi-scale hierarchy diagrams

Specification of

- Parameters
- Quantitative causal relations
- Decision/behavior rules
- Initial conditions

Reference mode reproduction

Matching of intermediate time series

Matching of observed data points

Constrain to sensible bounds

Structural sensitivity analysis

Parameter sensitivity analysis

Cross-validation

Robustness&extreme value tests

Unit checking

Problem domain tests

Specification & investigation of intervention scenarios

Investigation of hypothetical external conditions

Cross-scenario comparisons (e.g. CEA)

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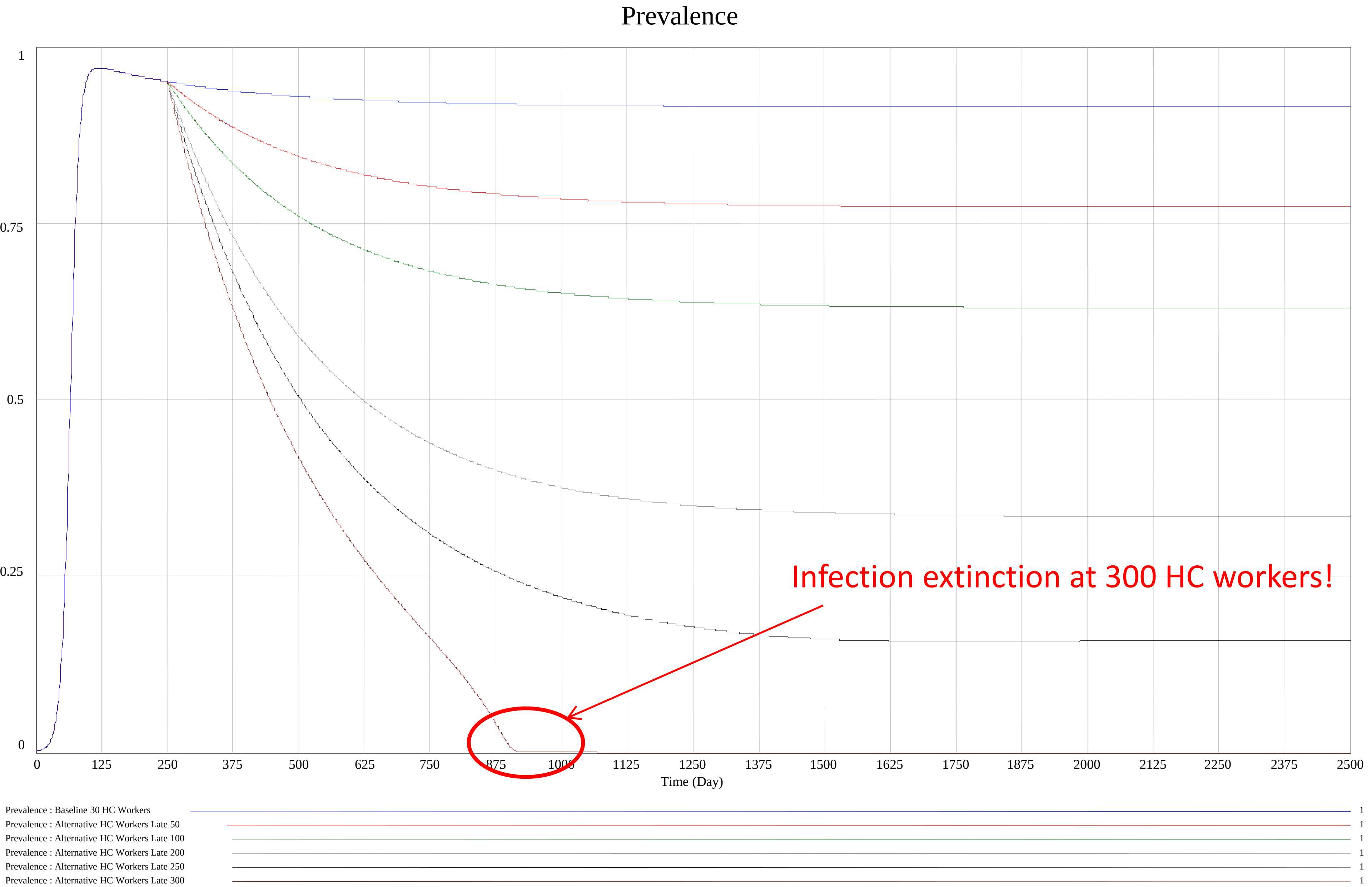
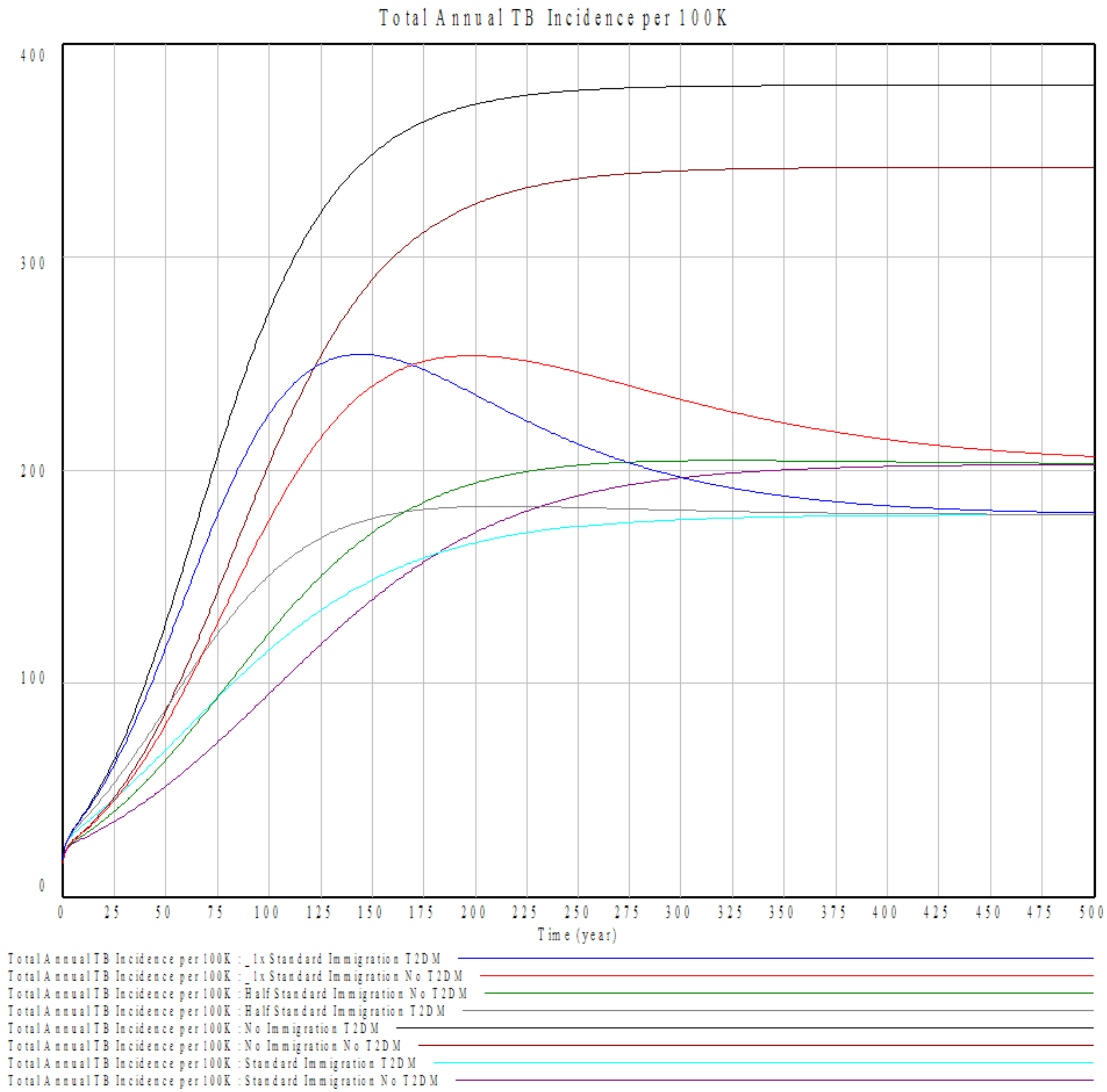
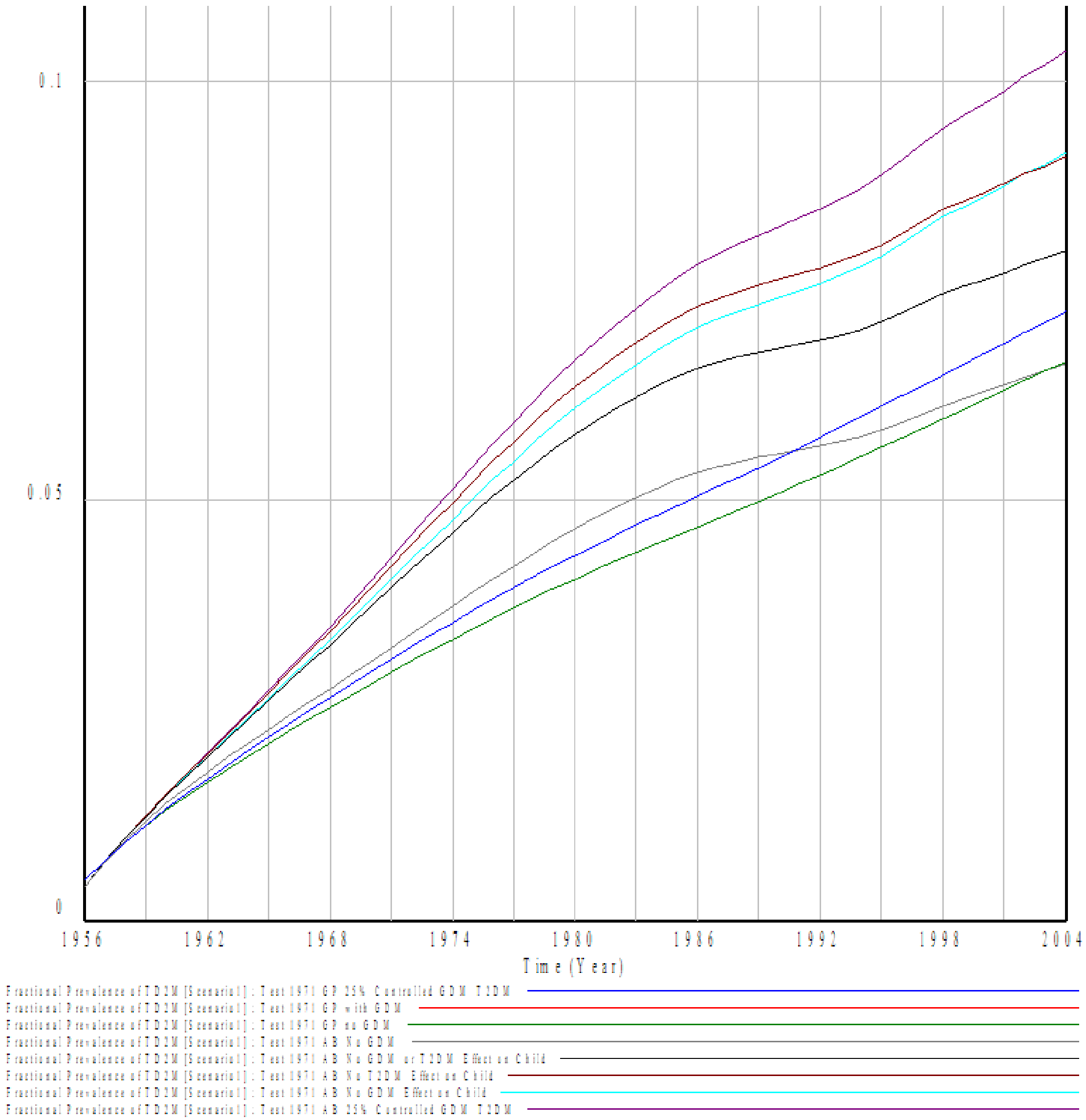
Late Availability of HC Workers



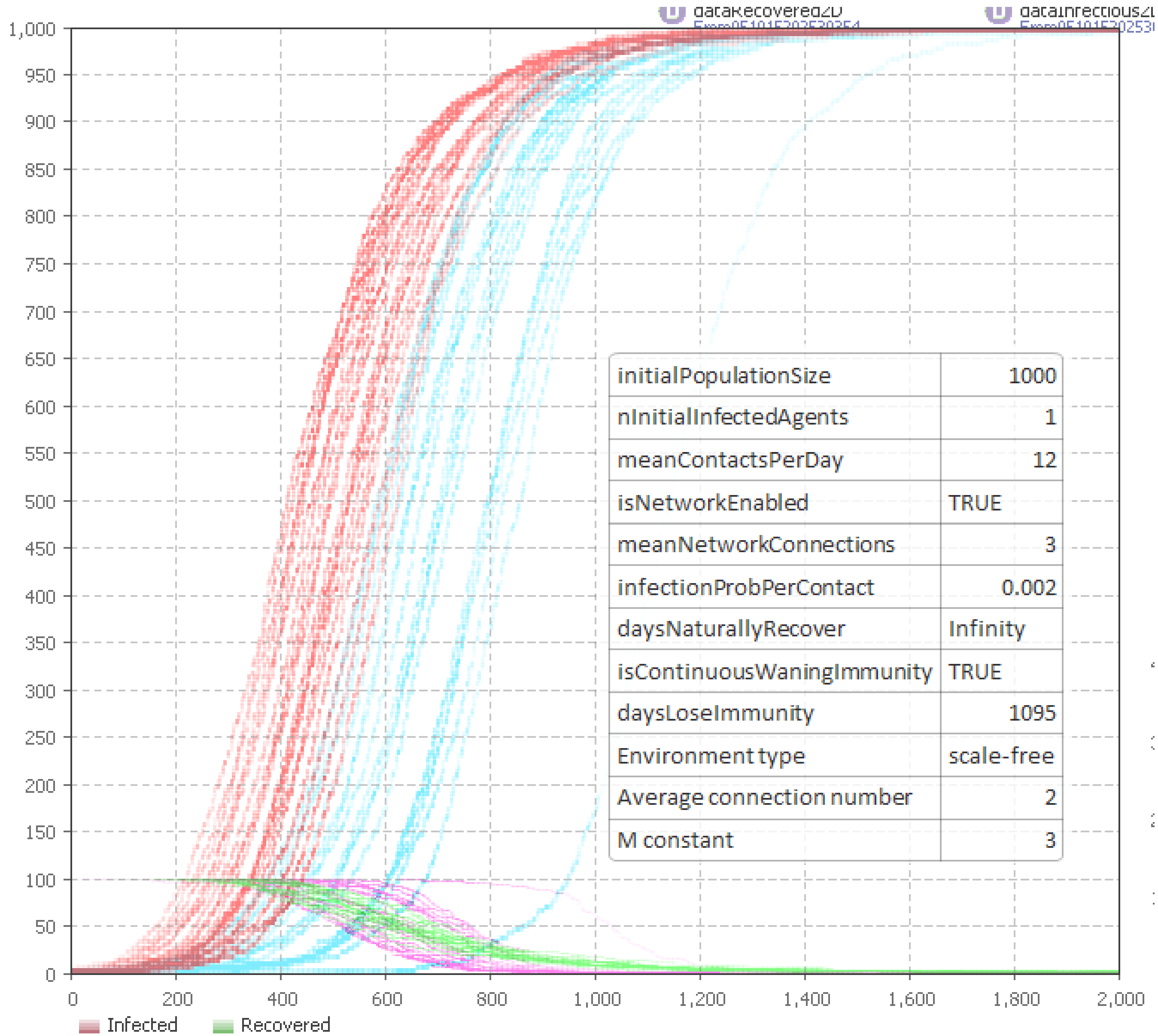
Simulation Analysis: Scenarios for Understanding How *X* affects System



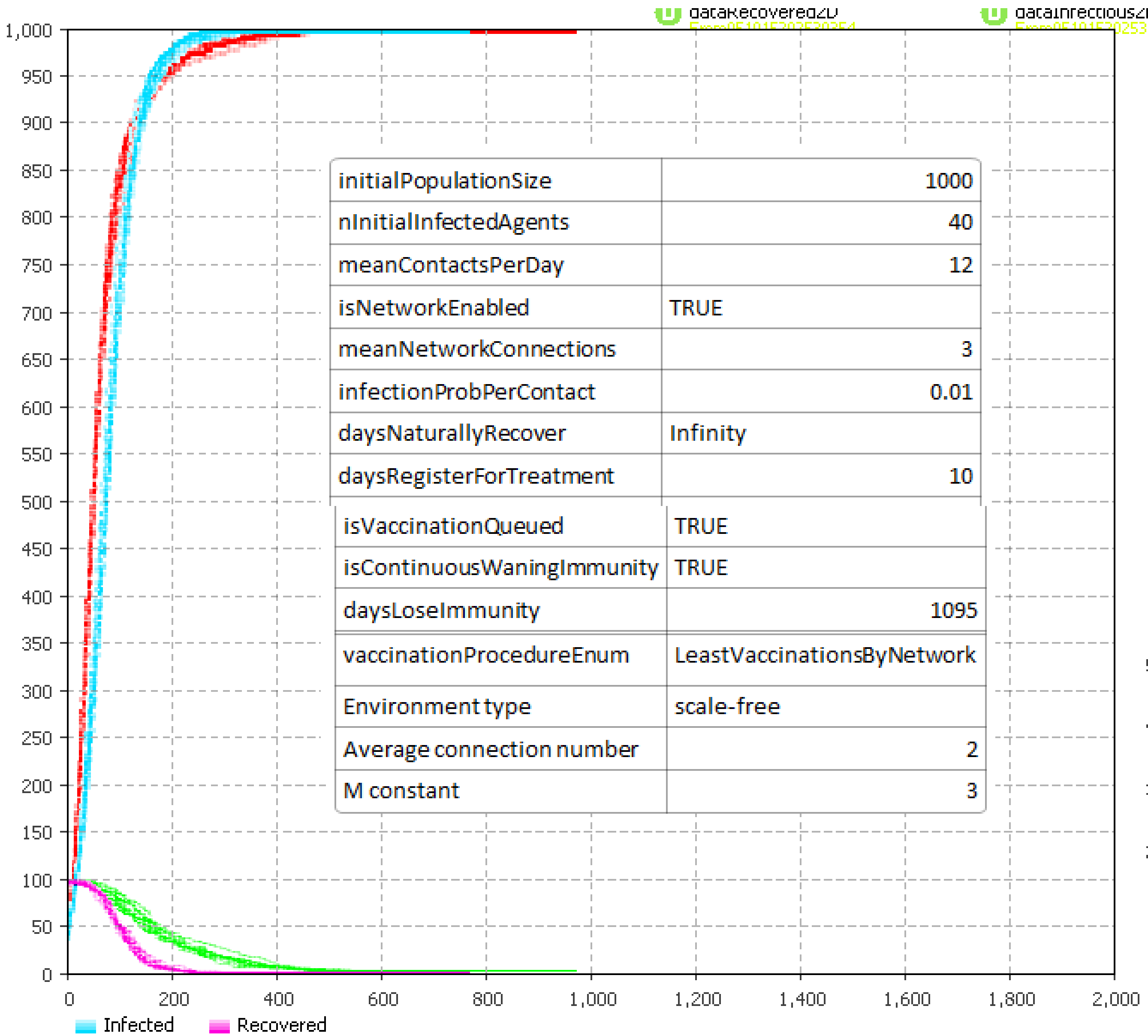
Policy Formulation & Evaluation



Policy Comparison: Stochastic Processes

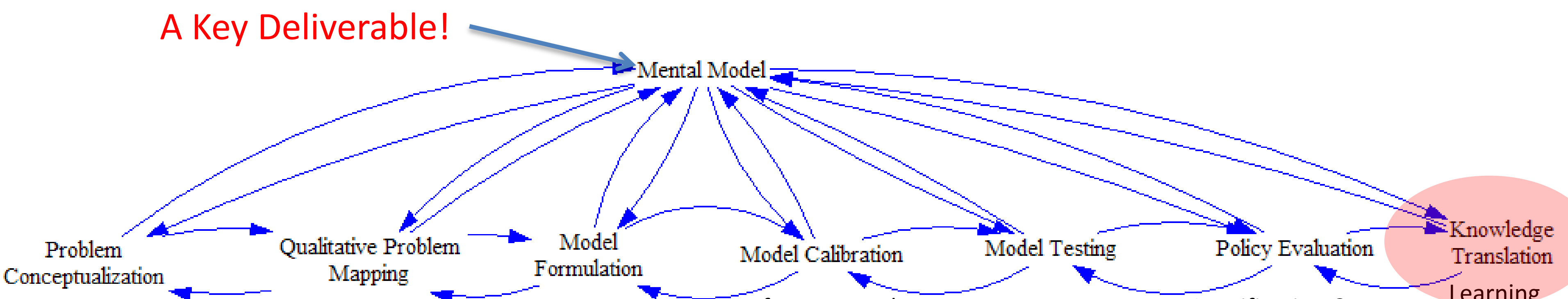


Policy Comparison: Stochastic Processes



initialPopulationSize	1000
nInitialInfectedAgents	40
meanContactsPerDay	12
isNetworkEnabled	TRUE
meanNetworkConnections	3
infectionProbPerContact	0.01
daysNaturallyRecover	Infinity
daysRegisterForTreatment	10
isVaccinationQueued	TRUE
isContinuousWaningImmunity	TRUE
daysLoseImmunity	1095
vaccinationProcedureEnum	LeastVaccinationsByNetwork
Environment type	scale-free
Average connection number	2
M constant	3

Modeling Process Overview



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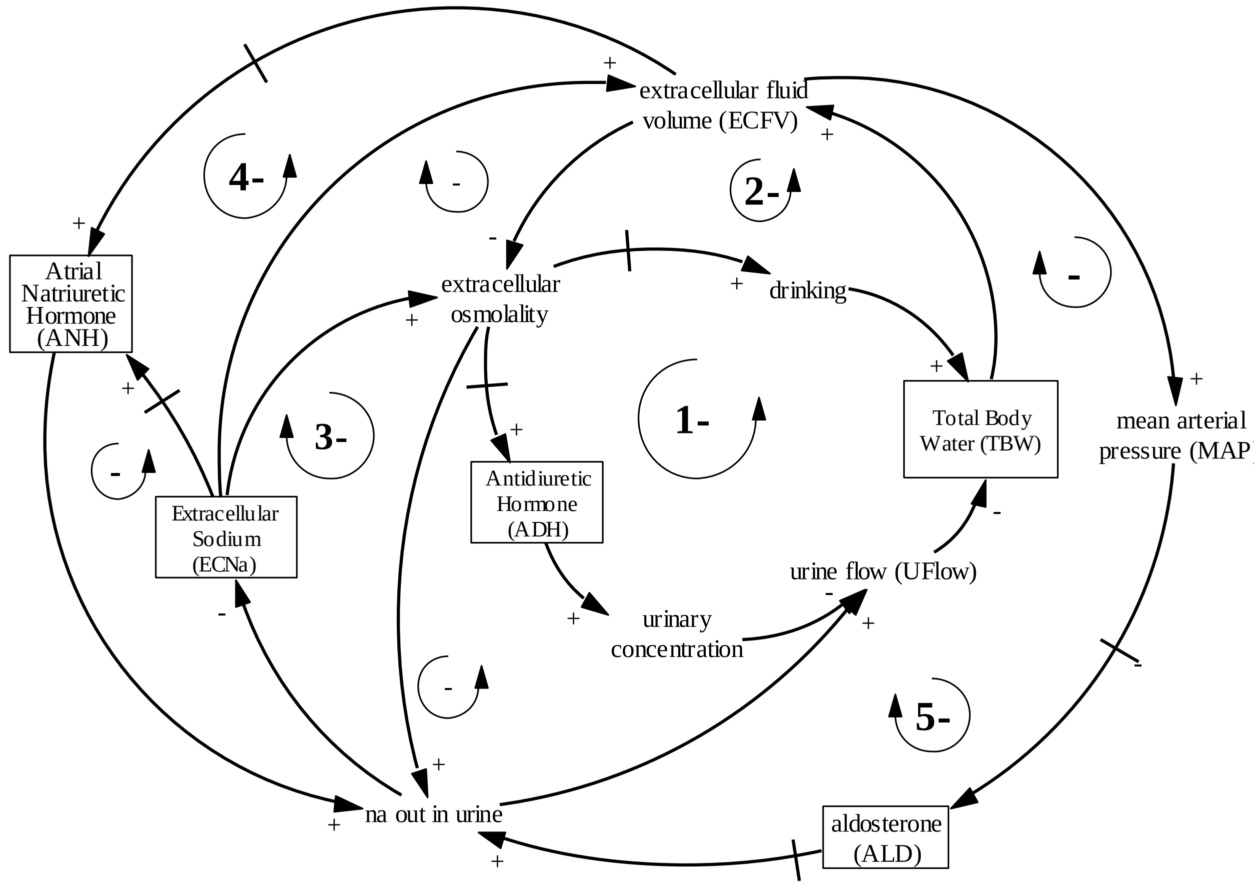
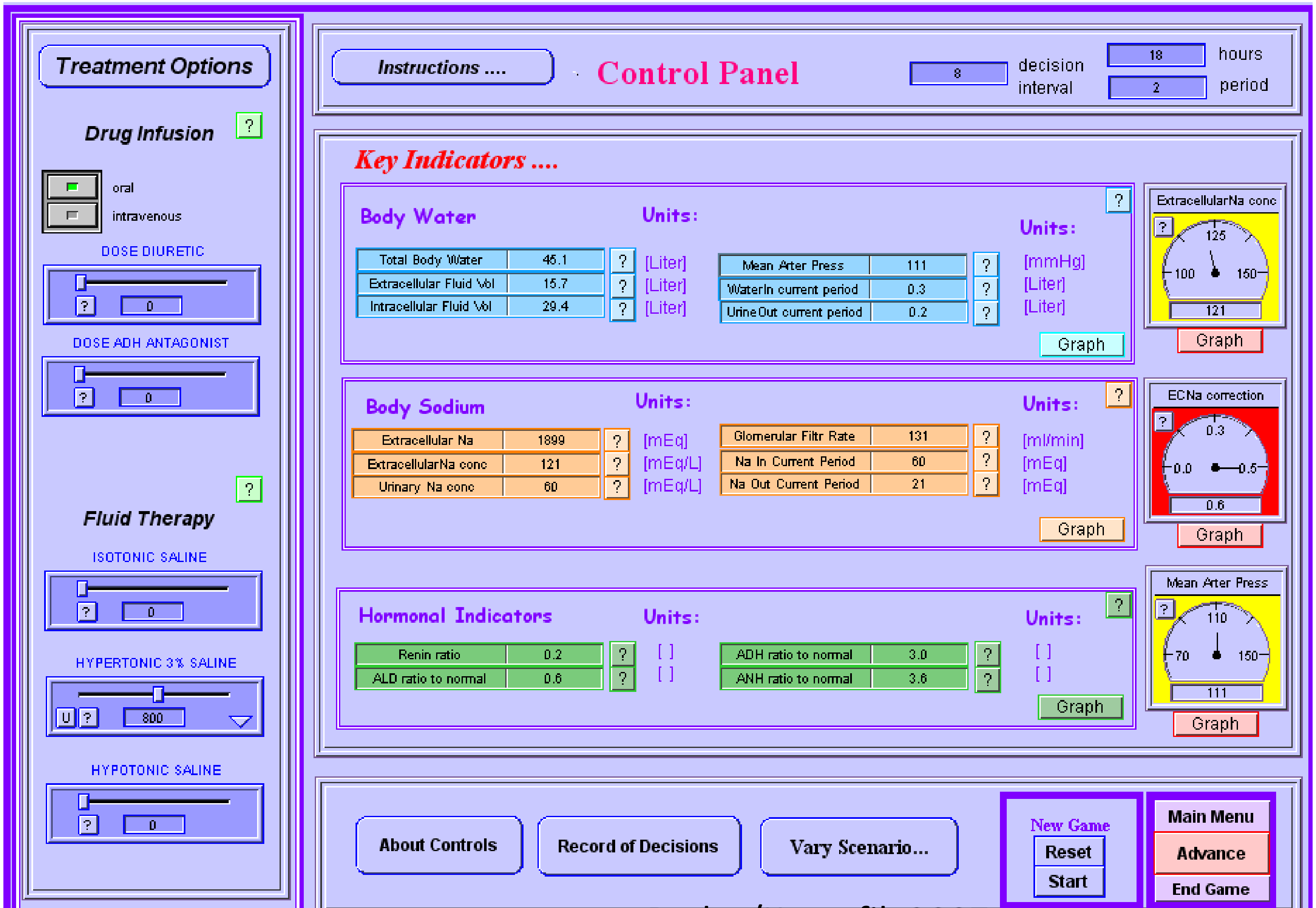
OVERVIEW OF THE MODEL



Simplified causal loop diagram of the overall model

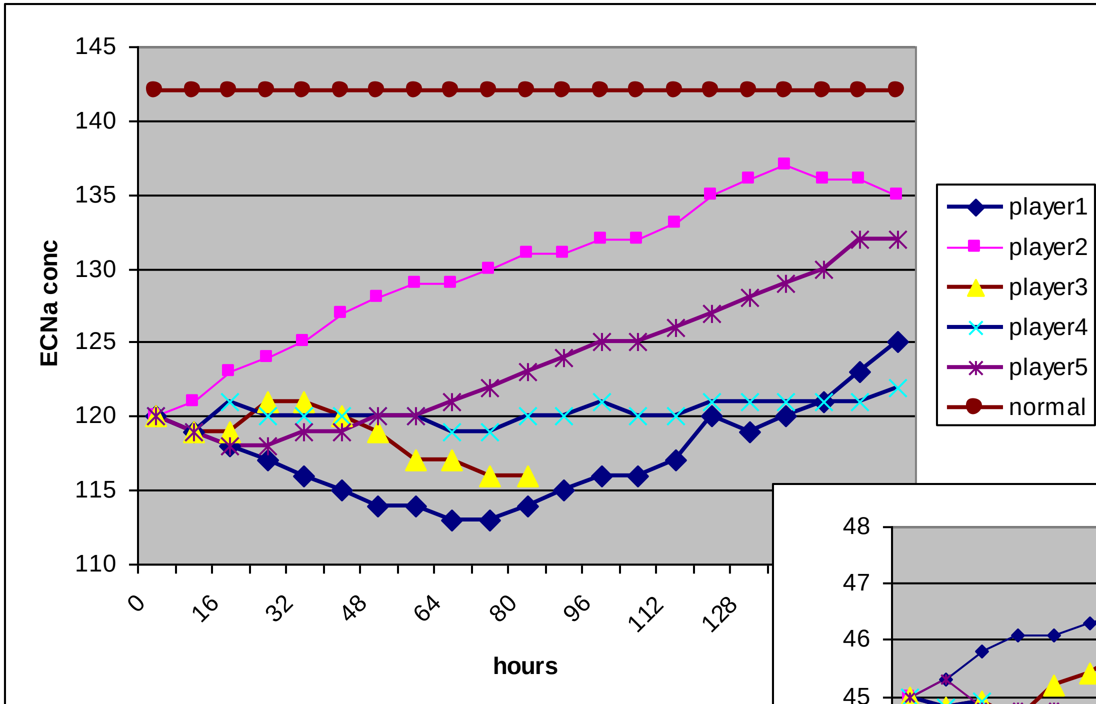
THE INTERACTIVE DYNAMIC SIMULATOR (BWATERGAME)



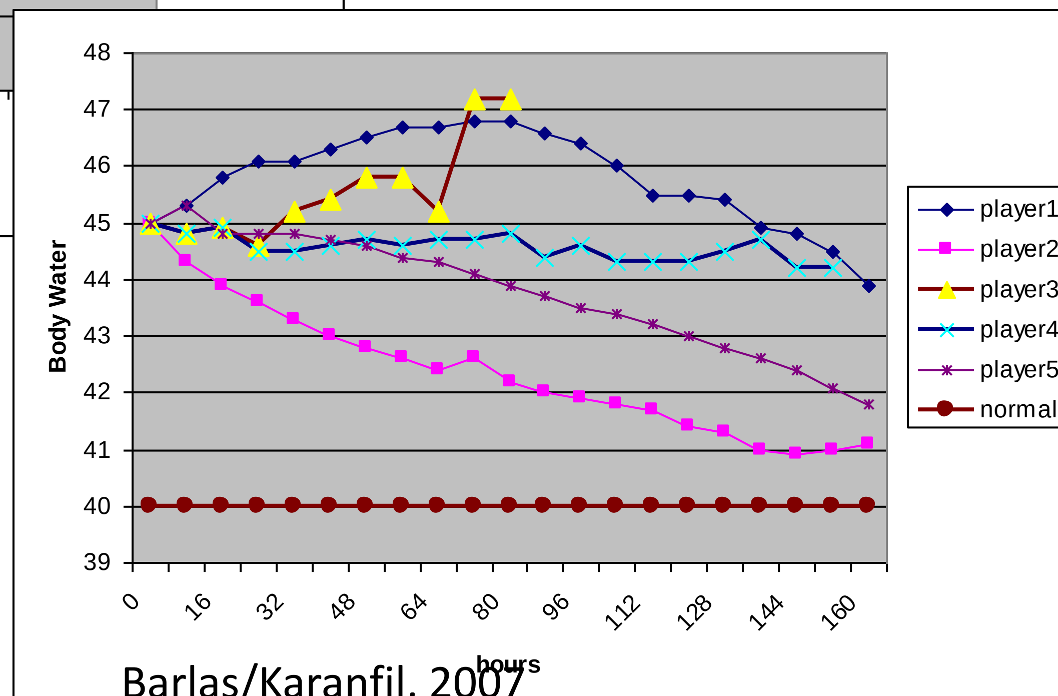
Barlas/Karanfil, 2007

Results of the Game Tests by Players

Dynamics of
ECNa concentration
for five players...



Dynamics of total body water...



Barlas/Karanfil, 2007

Stakeholder Action Labs

- Team Meetings

Mabry, 2009, "**Simulating the Dynamics of Cardiovascular Health and Related Risk Factors**"

Key Take-Home Messages from this Morning

- Models express dynamic hypotheses about processes underlying observed behavior
- Models help understanding how diverse pieces of system work together
- SD focus on feedbacks as the fundamental shapers of dynamics
- Models are specific to purpose
- System dynamics includes both qualitative & quantitative components
- SD models admit to formal reasoning & analysis