# SYSTEMS THINKING & SYSTEM DYNAMICS

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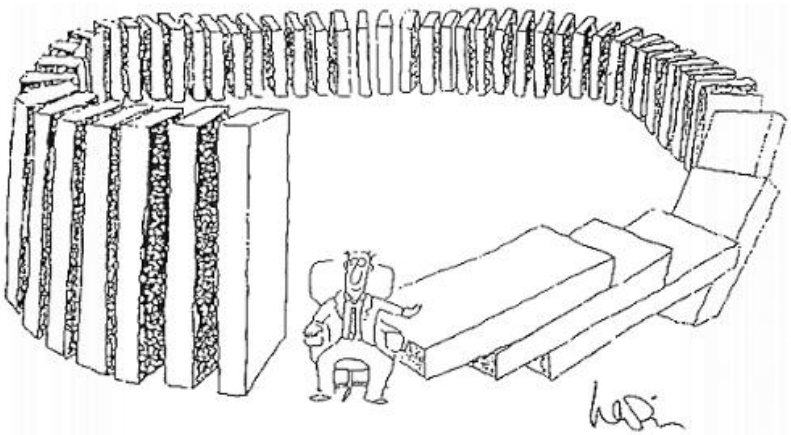
The evidence behind your decisions

# Cause and *delayed* Effect



Problem - Manager asked to create more space,
Solution - He did with a small push,
Effect - He gets promoted & his successor …

Challenges?
- Cause and Effect not clear
- Delay between Cause & Effect
- Compounding effect

Deep understanding of fields *requires* relating <u>structure</u> & <u>function</u>

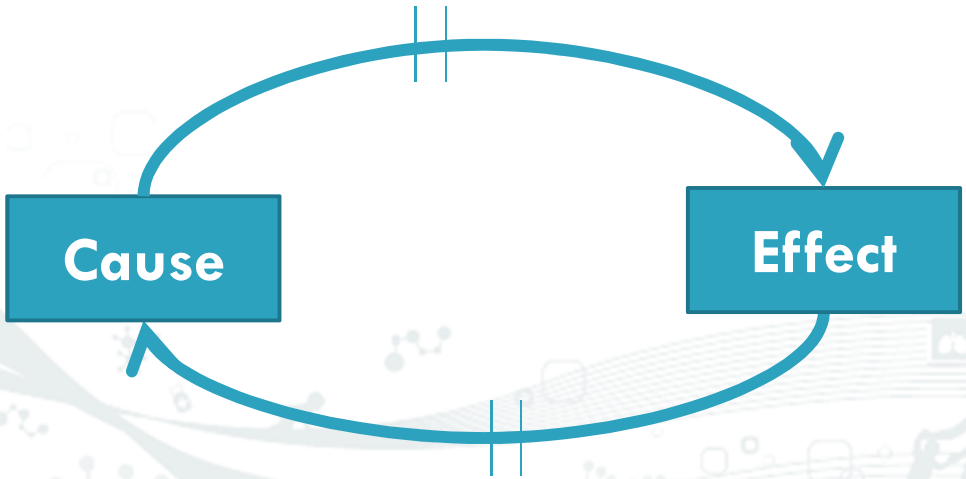
- Protein structure & function
- Data structures & algorithms

* Infectious disease parameters & spread
* Circuit design & performance

Leads to better DESIGN or DIAGNOSIS

# What is a System?

- A system has components but the relationships among them can create complex overall behavior.




- We are interested in a systems analysis tool that addresses feedback loops: cause -> effect -> cause
- Tool: Systems Thinking and System Dynamics

# Outline

Big picture

1. Our interest is on Systems with feedback structures -> behavior
2. Where we will use Systems Thinking & System Dynamics tools
3. To diagnose *Policy resistance in which we*

Patterns

1. Identify 4 basic dynamic behavior patterns & equations,
2. Map out causal loop diagrams,
3. Reusing known System patterns

Quantitative, Leverage & Applications

1. To quantify, getting Stocks and Flows right
2. And see applications: MRSA infection dynamics, Hospital dynamics
3. Look for leverages.

# Systems Thinking and System Dynamics

The central concept is that a system's dynamic behavior is caused by feedback structures

- Earlier we saw
  a) Positive Feedback as Self-reinforcing/Growth &
  b) Negative Feedback as Self-correcting/Regulation.

- Feedback structures are found in Natural, Engineering and Organizational systems. For example:

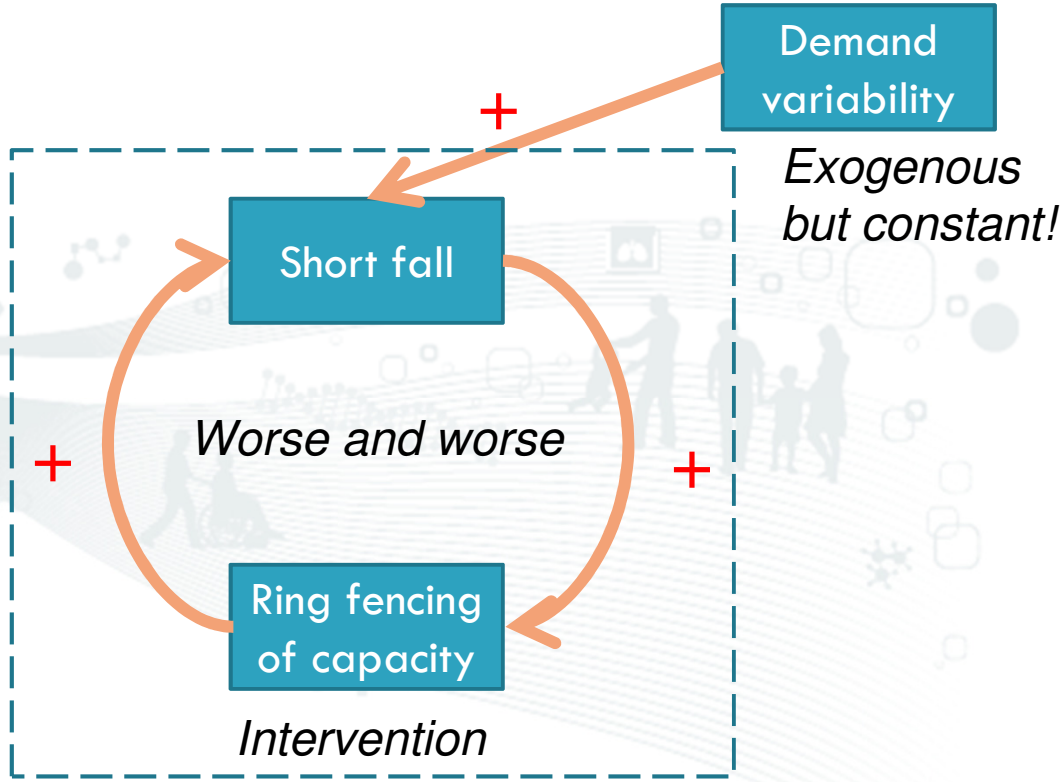
| **Systems** | **Control** |
|---|---|
| | Negative feedback |
| Health | Body temperature |
| Engineering | Automation |
| Organization | Management |

# Policy resistance (1)
# - *where our solutions make the problem worse*

- Variability in demand for common resources can lead to shortfall/surplus/wait time for departments. This may prompt dedicated/splitting of resources. Actually this can worsen the shortfall/surplus/wait. If we tighten further with more rules we can make it worse.

*Common resources*
Budget?
Shared manpower?
Inpatient beds?
Machine time?

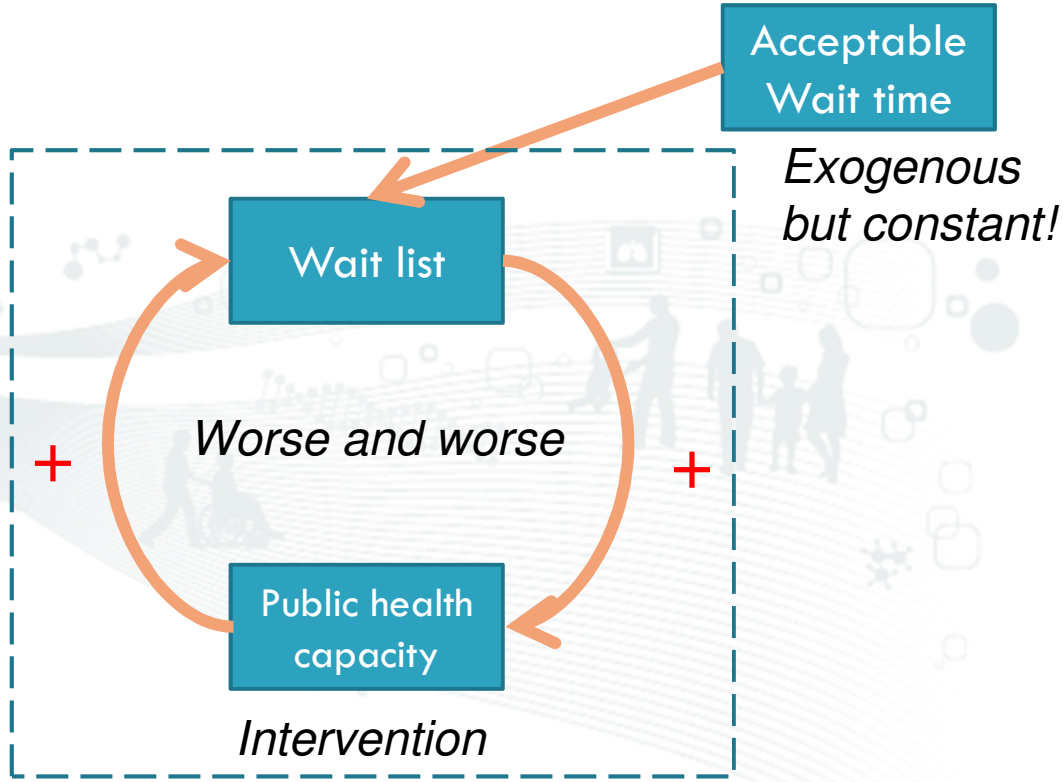
Pooling resources?



# Policy resistance (2)
# - *where our solutions make the problem worse*

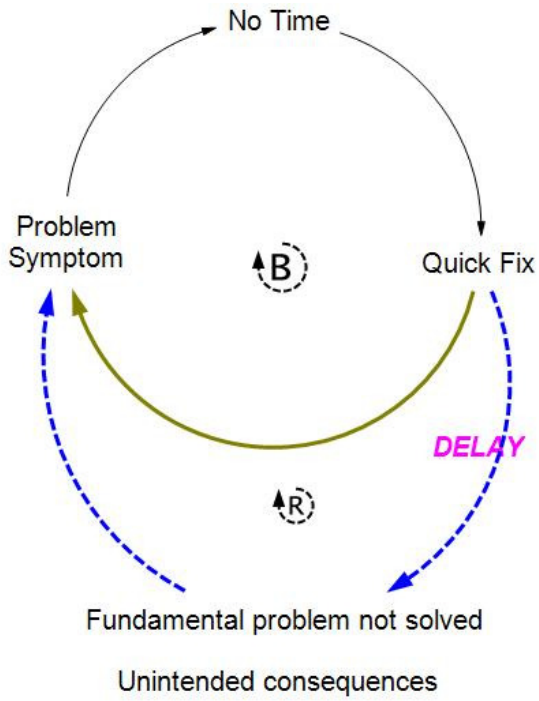
- Given a long wait list, public healthcare capacity is increased. After a short term improvement, this stimulates further demand resulting in long wait list again.

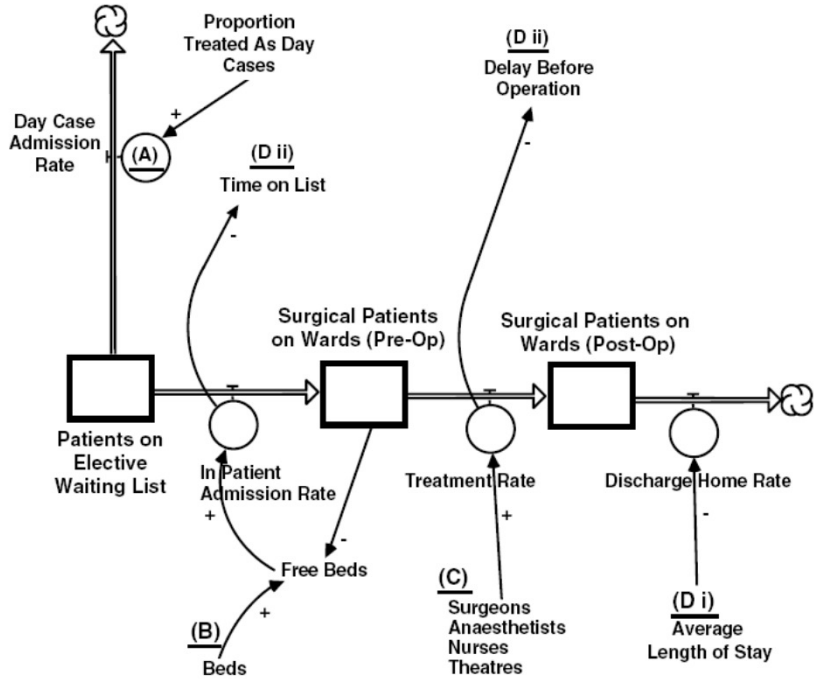
Supplier induced demand when bill is publicly footed



# Systems Thinking (qualitative)

# System Dynamics (quantitative)






$$\begin{cases} \dfrac{dx}{dt} = 2x - 1.2xy \\[2ex] \dfrac{dy}{dt} = -y + 0.9xy \end{cases}$$

# Use what you learn to …

- *Understand*
  - why systems behave as they do in the short and long term.
- *Share*
  - your understanding of a causal model of a system with feedback structure.
- *Change*
  - if we can improve the current intervention cost effectively.

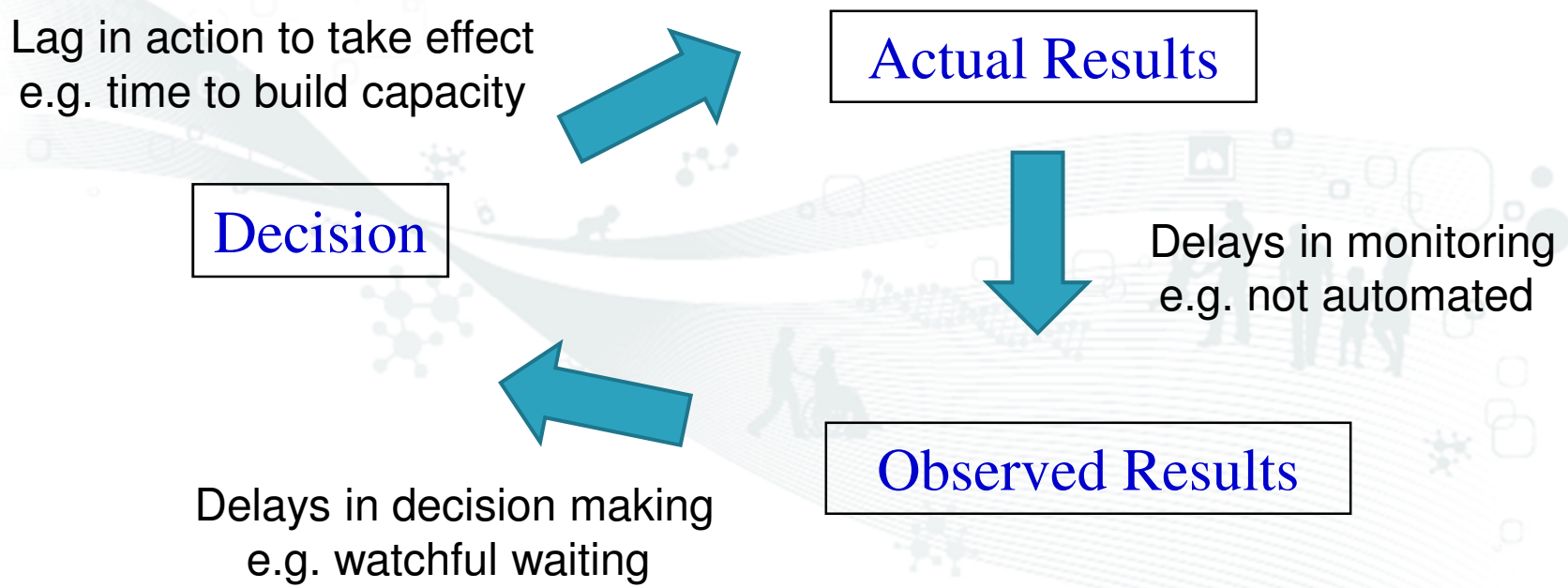
# Concept 1 – Feedback (Cause → Effect → Cause)

- Positive feedback
  - + is known as self-reinforcement loop (R)
  - + can be
    - Vicious cycle (bad becomes worse)
    - Virtuous cycle (good becomes better)

- Negative feedback
  - + is a balancing or balancing or self-correcting loop (B)

# Concept 2 – Delays

- Delays lead to over/under correction (oscillations)
- Delays are due to:



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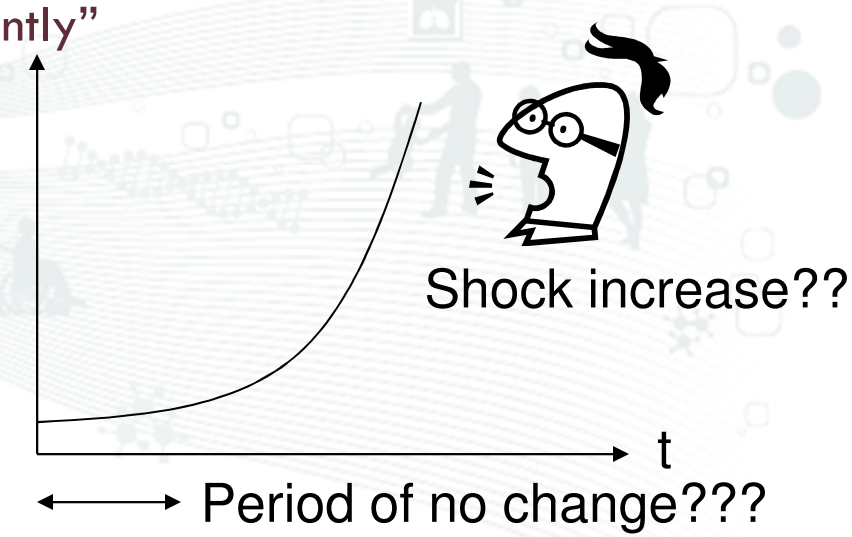
# 1. Exponential growth
# Positive feedback structure

- Key points
  - Caused by positive feedback
  - Can be growth or decline

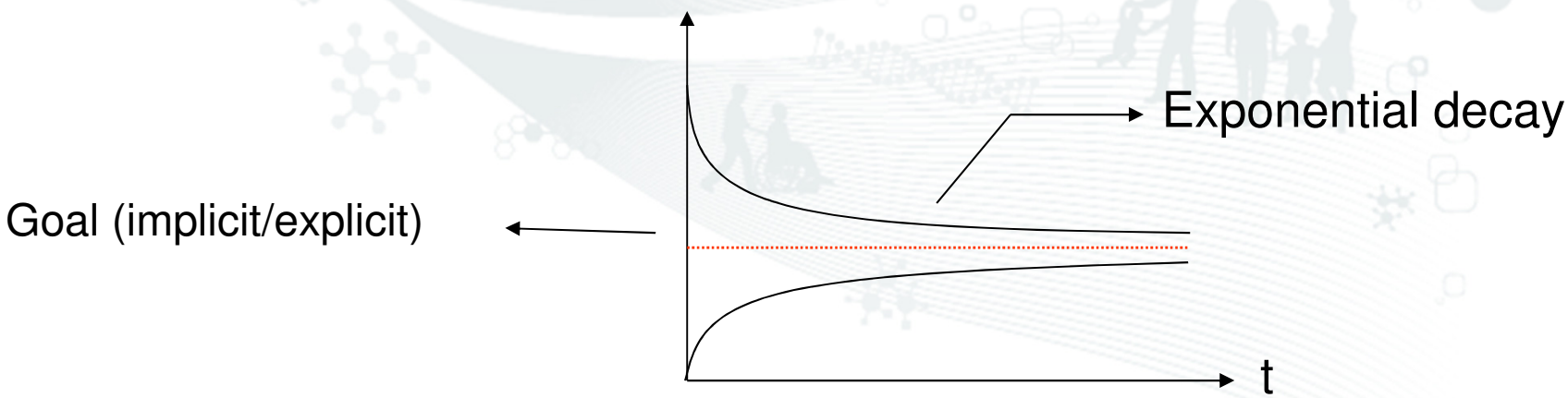
**Isn't this what we want for corp growth?**
**Additive or Multiplicative process?**

- Identifiers
  - System reinforces itself, feeding onto itself, exponential growth, virtuous cycle, vicious cycle …
  - "There is 'no change' for most of the time and suddenly it shot up, something must have happened recently"
- Examples
  - 5 %/year growth
  - Principal + compounding interest
  - Infectious disease outbreak



# 2. Regulation/Balancing/Goal seeking Negative feedback structure

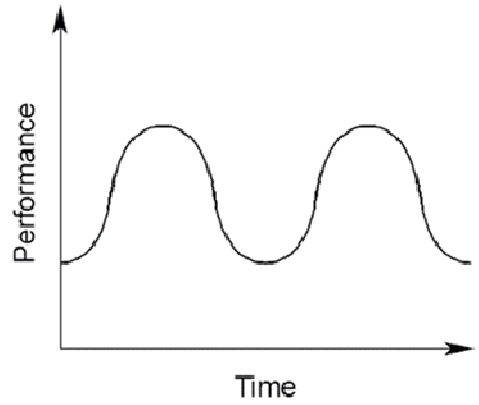
- Key points
  - + Caused by negative loops/corrective action
  - + Brings state of system inline with goal/equilibrium
  - + There is a measurement of state and 'info' feedback
- Examples
  - + Reaching and meeting KPIs



# 3. Oscillation due to delays
# Negative feedback with delays

- Key points
  - + Caused by negative feedback loops with time delays
  - + We saw the 3 times delays (???)
  - + Can remain as cycles, die down or inflate depending on

- Identifiers
  - + Significant delays in a corrective process



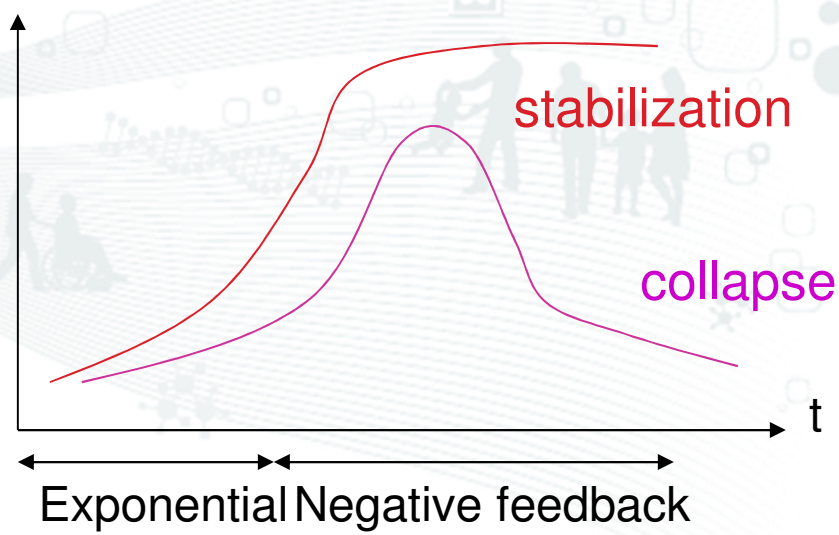
d. Oscillation

# 4. S-shaped
# Positive and Negative feedback

- Key points
  - Rapid rise followed by stability
  - Exponential growth followed by a negative feedback process
- Identifiers
  - Positive and negative feedback structures acting together
  - When there is positive feedback there are natural limits

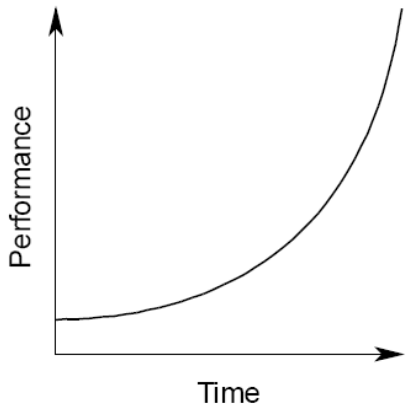
**When rising, our concern is (will/when) there be tipping point?**

**2 organizations could be at different points in same trajectory.**



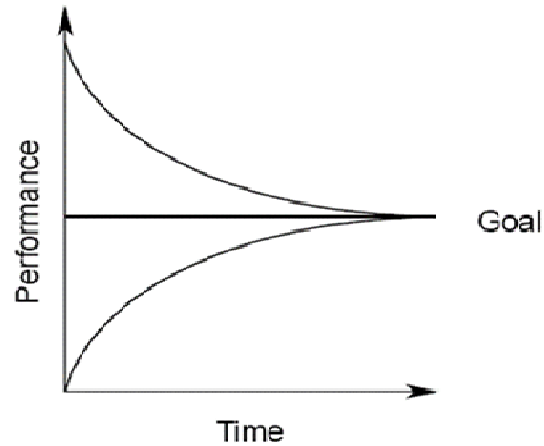
# The equations for the 4 patterns: differential equations





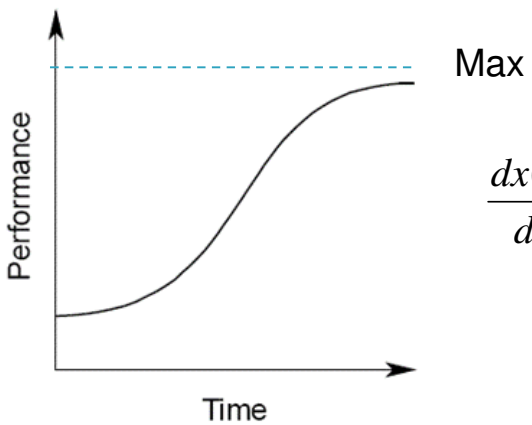

a. Exponential growth

$$\frac{dx(t)}{dt} = x(t)$$



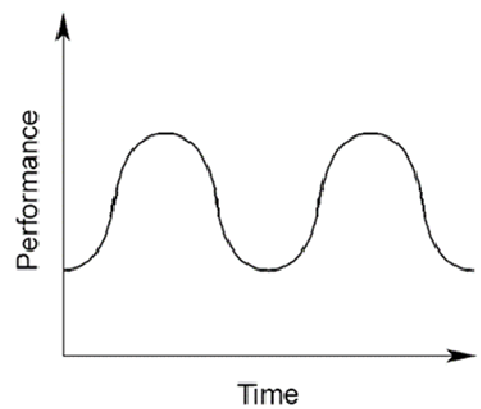

b. Goal-seeking

$$\frac{dx(t)}{dt} = T\arg et - x(t)$$




c. S-shaped

$$\frac{dx(t)}{dt} = x(1 - \frac{x}{Max})$$




d. Oscillation

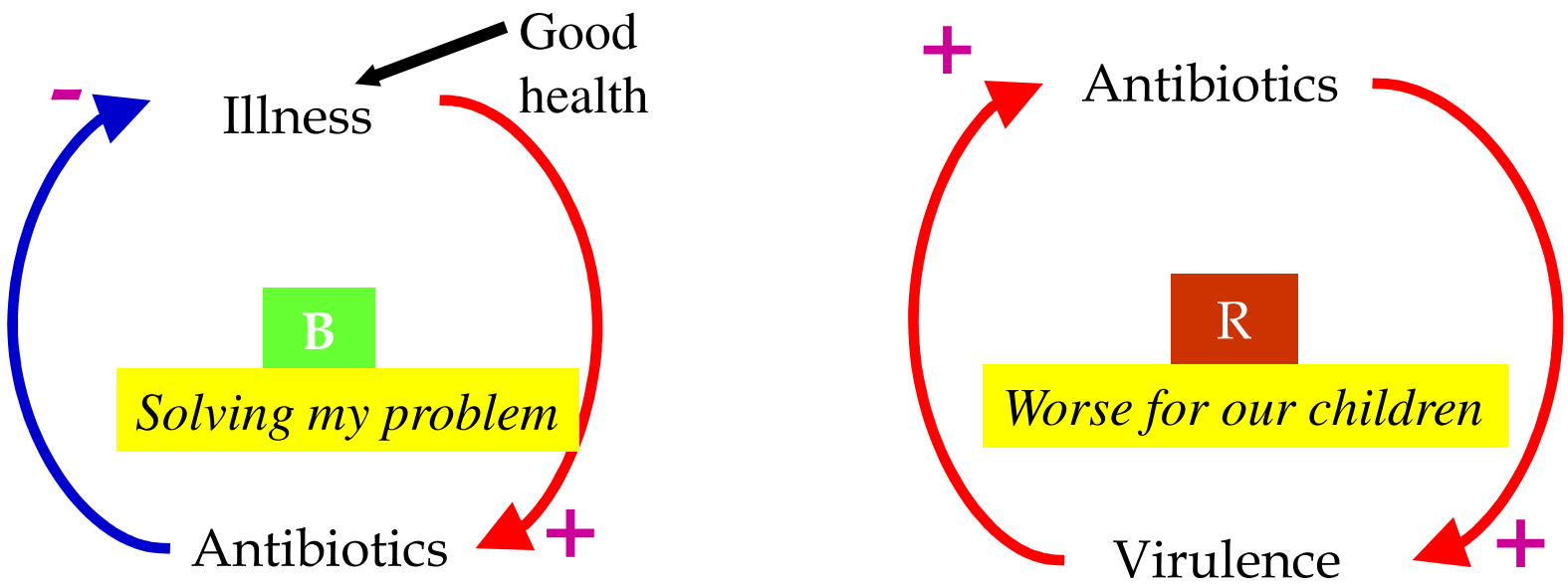
$$\frac{\mathrm{dx(t)}}{\mathrm{dt}} = \mathrm{T\arg et - x(t - Delay)}$$

## Identifying Balancing and Reinforcement processes

We develop an infection and are prescribed antibiotics and complete the course and become well. In the long term, the virulence increases and we have to take stronger courses to fight it off.

1. How many feedback structures are there?
2. What are they?

# Causal Loop Diagram for mapping feedback and delays




"+" means that when the starting variable increases, the second one increases also

"-" means that the starting variable increases, the second one decreases

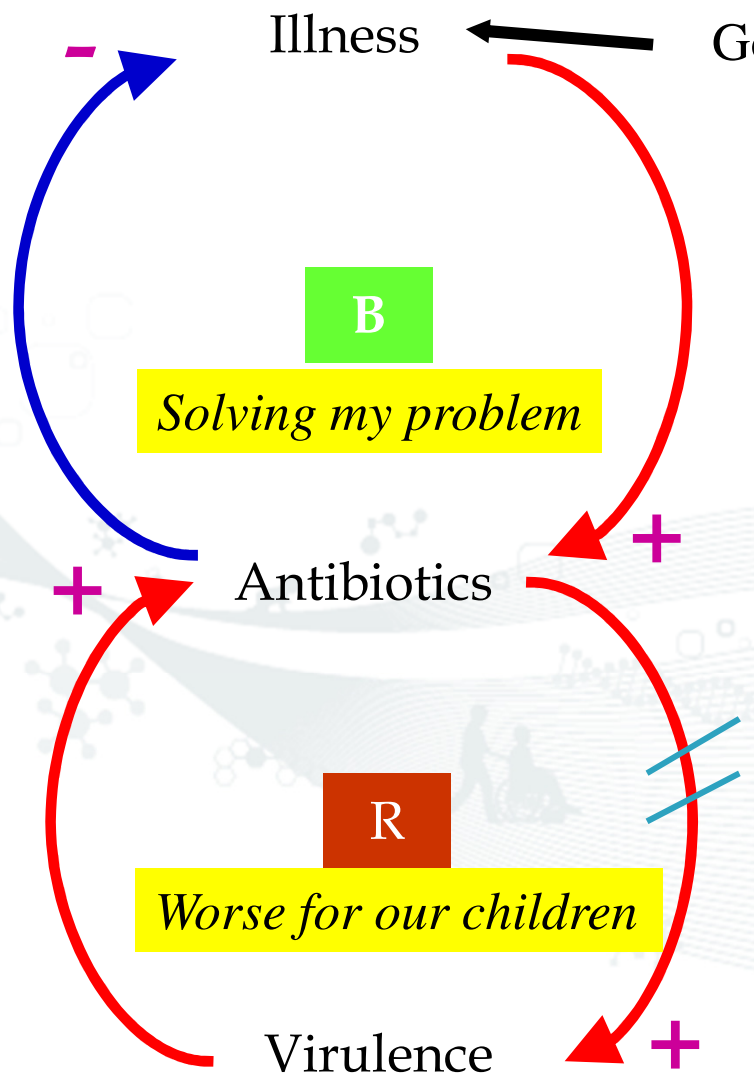
"R" means reinforcing; i.e., the causal relationships within the loop create exponential growth or collapse

"B" means balancing; i.e., the causal influences in the loop keep things in equilibrium

# Putting together…

Description

We develop an infection and are prescribed antibiotics and complete the course and become well. In the long term, the virulence increases and we have to take stronger courses to fight it off.




System structure

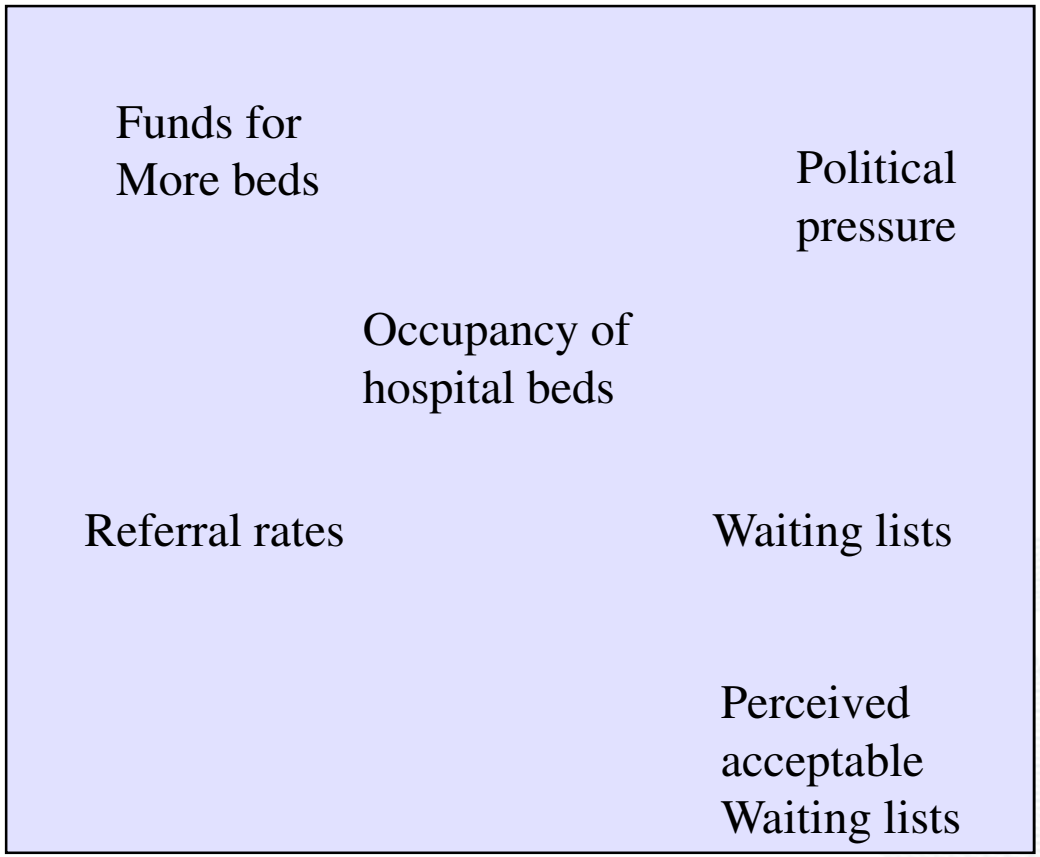
Biochemical intervention against susceptible organisms.

Selective pressure to evolve.

# Some guidelines for diagramming

- Framing
  - Choose right level of aggregation and long term perspective
  - Think of current situation and desired situation (with intervention)
  - Reuse existing system archetypes, if relevant
- Development of CLD
  - A link should represent causal relation not correlation
  - Focus on 1 pair of variables at one time (ignore the rest)
  - Focus on 1 loop at one time (ignore the rest)
- Development of CLD (cont'd)
  - Variable naming
    - Use nouns or noun phrases (no verbs or pre fix with increase/decrease etc.)
    - Must have clear sense of direction (can increase or decrease)
    - Normal sense of direction is positive (not patient dissatisfaction, losses)
  - Name each of the loop as shorthand
  - Indicate major delays on the links
- Iteration
  - Create 1 small loop with 2 or 3 variables
  - Create intermediate variables later

# Let's draw causal loops.
# - the dynamics of referral, BOR and wait lists




System Dynamics: What's in it for healthcare simulation modellers,
Winter Simulation Conference 2008, Sally S. Brailsford

The system shown here is the process by which patients are admitted. Long wait lists are a political issue.

Exercise

1. Study the factors
2. Identify the cause/effects
3. Indicate polarity with +/-
4. Identify feedback type (B/R)
5. Explain the story ☺

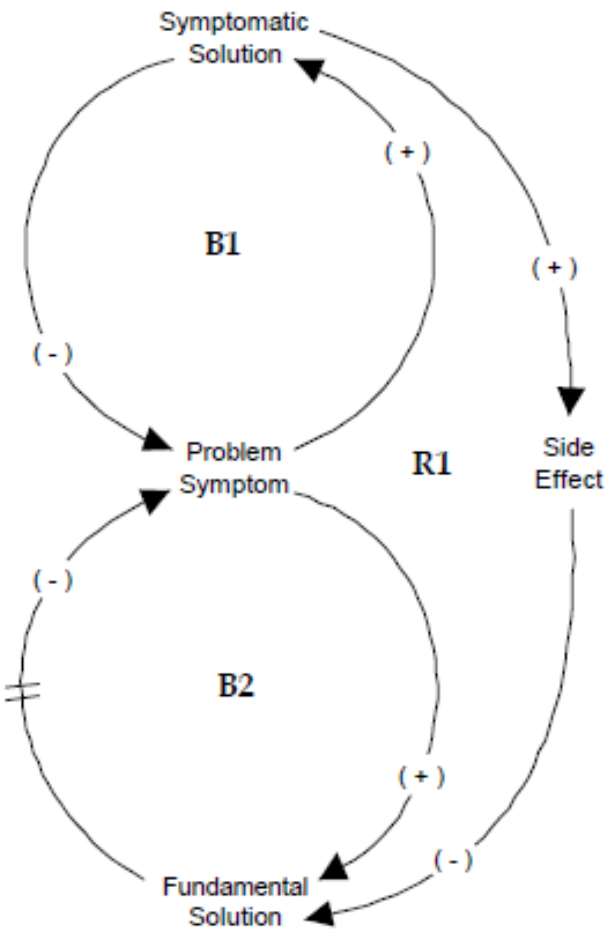
# System Archetypes[1]

- System Archetypes are common patterns of organizational behavior. Useful for framing new issues, short term fix, long term solutions and side effects.

- Limits to Growth/Success
- Shifting the Burden
- Eroding Goals
- Escalation
- Success to the Successful
- Tragedy of the Commons
- Fixes that Fail
- Growth & Underinvestment
- Accidental Adversaries
- Attractiveness Principle

*1 - The System Archetypes by William Braun (2002) www.uni-klu.ac.at/~gossimit/pap/sd/wb_sysarch.pdf*

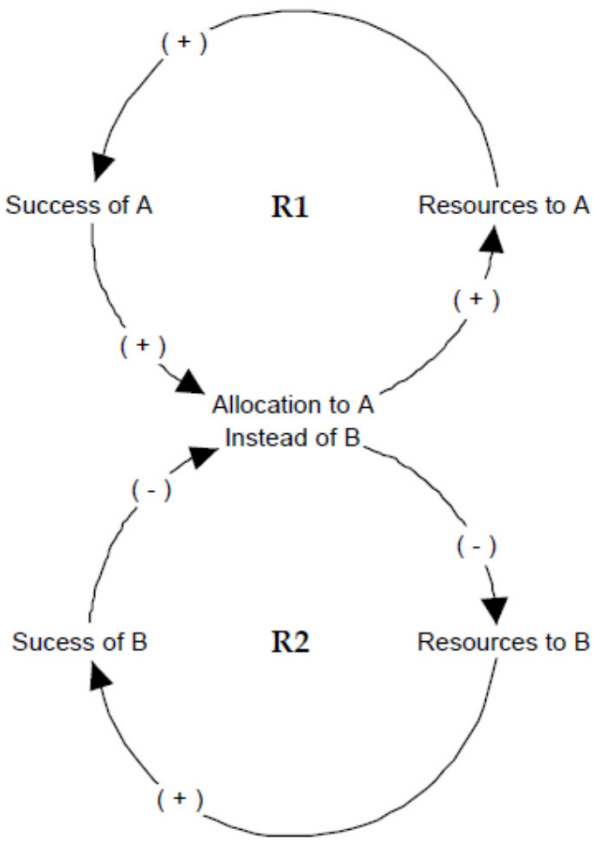
# Shifting the Burden
## - organizational addiction




**Generic Archetype**

- Heroes will emerge to solve crises in healthcare and will be depended upon to save the day.
- Creates '*organizational addiction*' and less incentive to system solution, since it's available.
- The leverage is to learn and implement or spread out the solution approach.

# Success to the Successful
## - self fulfilling prophesy




**Generic Archetype**

- We start 2 service line A and B and have hopeful optimism.
- A gets some success and B doesn't and we feed A with more resources (at expense of B).
- A grows further, B declines and soon we close B and champion A.
- Could be true. But maybe the initial conditions could be quite at chance. What if B had actually had greater margins?

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# System Dynamics analysis

- ST is useful for qualitative analysis. But quantitative modeling may be needed to know the magnitude and direction of effects.

- Though we can only focus on dynamic trends and not point predictions.

- It requires good understanding of Stock and Flow concepts for visual modeling first. So we begin with 'stock and flow'.

# Identifying Stocks and Flows

| System description | Stocks | Inflow | Outflow |
|---|---|---|---|
| Medical resource library | Books | Returning, new books bought | Borrowing, discarded, lost |
| Diabetes prevalence | | | |
| My healthcare knowledge | | | |
| Blood bank | | | |
| Doctors supply and demand | | | |
| Flow of SOC patients | | | |

# Understanding stock and flow (1)



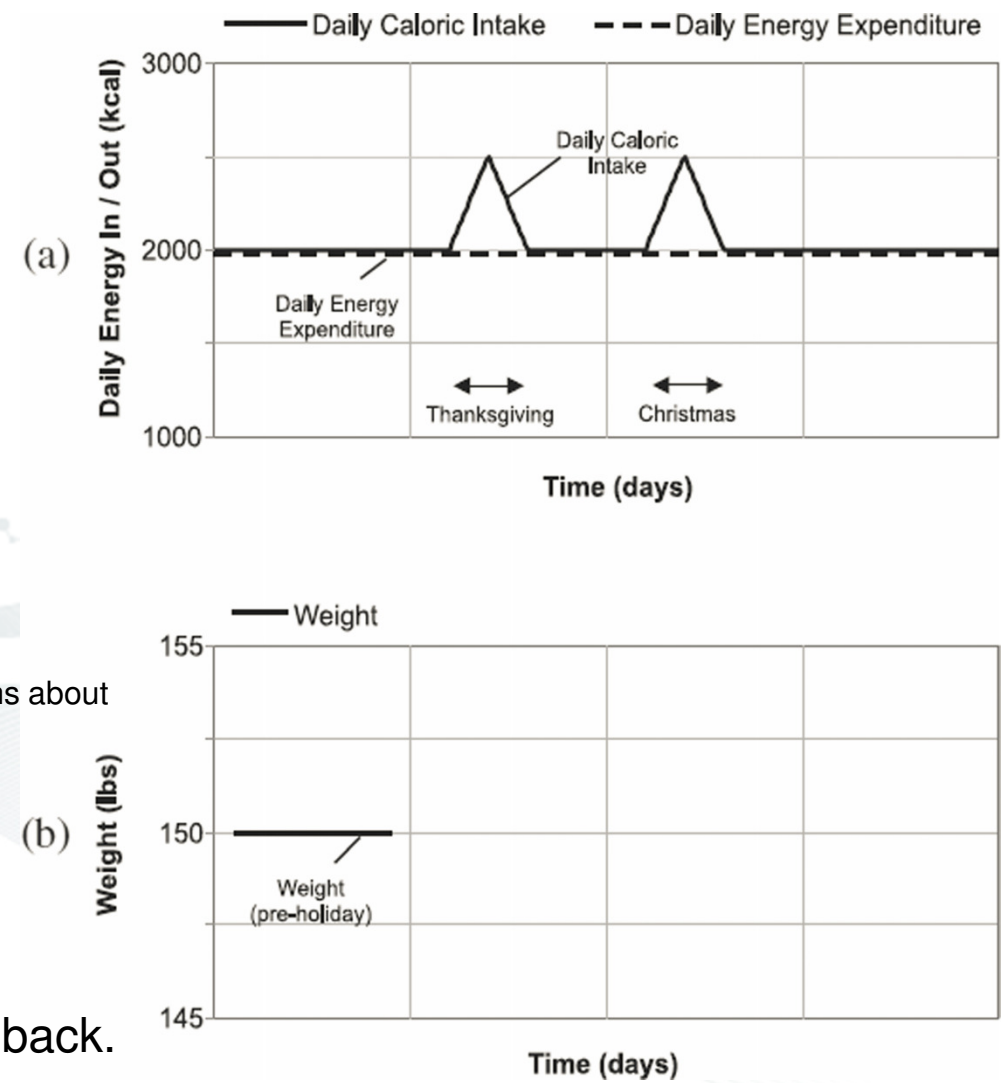
- Everyday 50 patients are admitted for a case of outbreak. Their average stay is 10 days.

a. How many beds are needed if the 'constant' epidemic lasted <u>for 30 days</u>?

b. How many beds are needed if the constant epidemic lasted <u>for ever</u>?

# Understanding stock and flow (2)

- We indulge a bit during 2 holidays. Increasing intake before, peaking and decreasing after the day.
- Our energy expenditure is the same.
- What's the weight pattern?



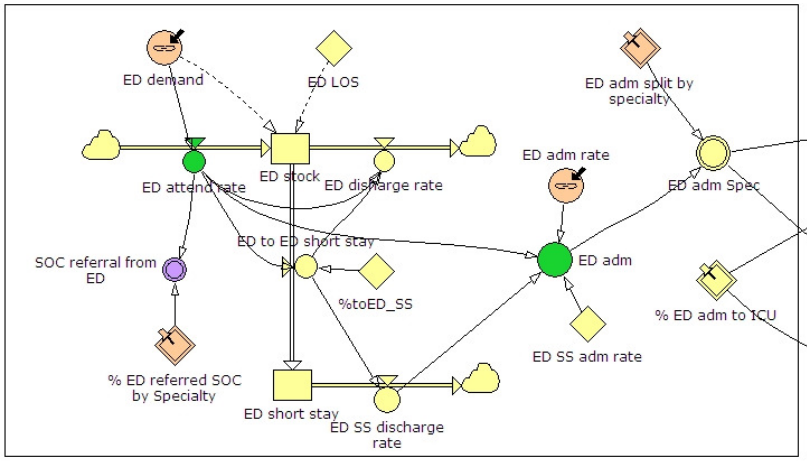

Tarek et.al. Public and health professionals' misconceptions about the dynamics of body weight gain/loss.
System Dynamic Review. (2014); 30(1-2): 58-74

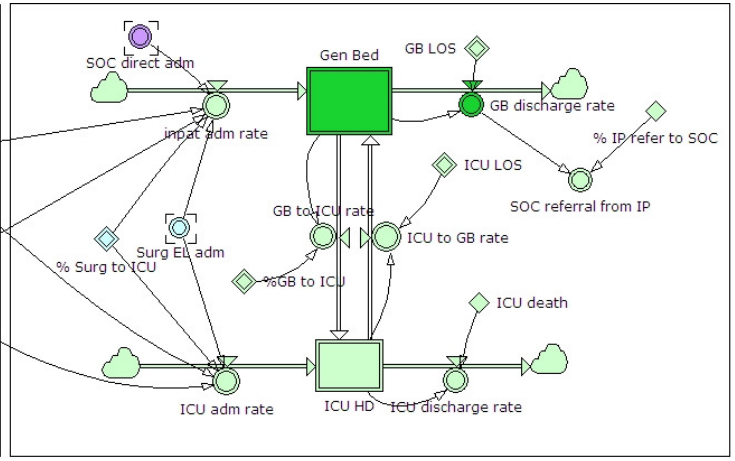
But both are simple cases with no feedback.

# Examples

- Hospital patient/information flow dynamics.
- Infectious disease transmission at population level (mathematical epidemiology).
- Glucose-Insulin dynamics at patient level (mathematical biology).

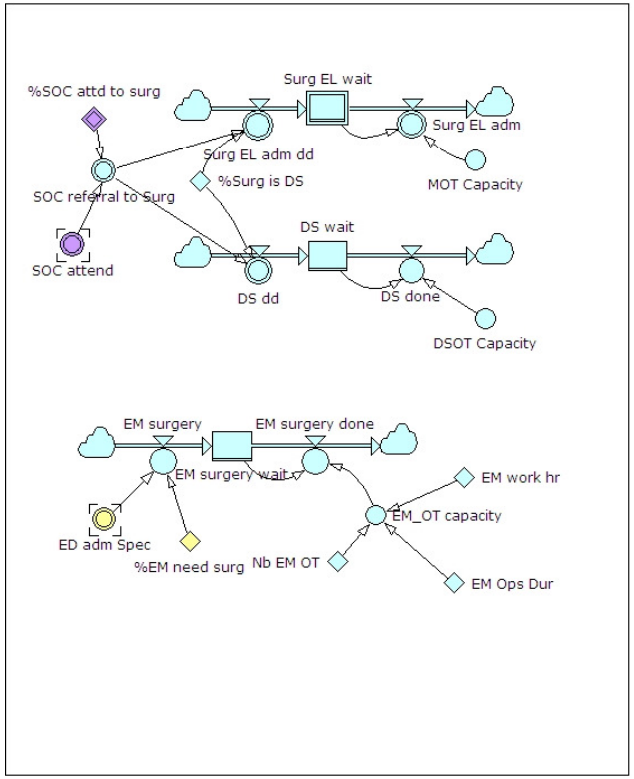
# Hospital patient flow

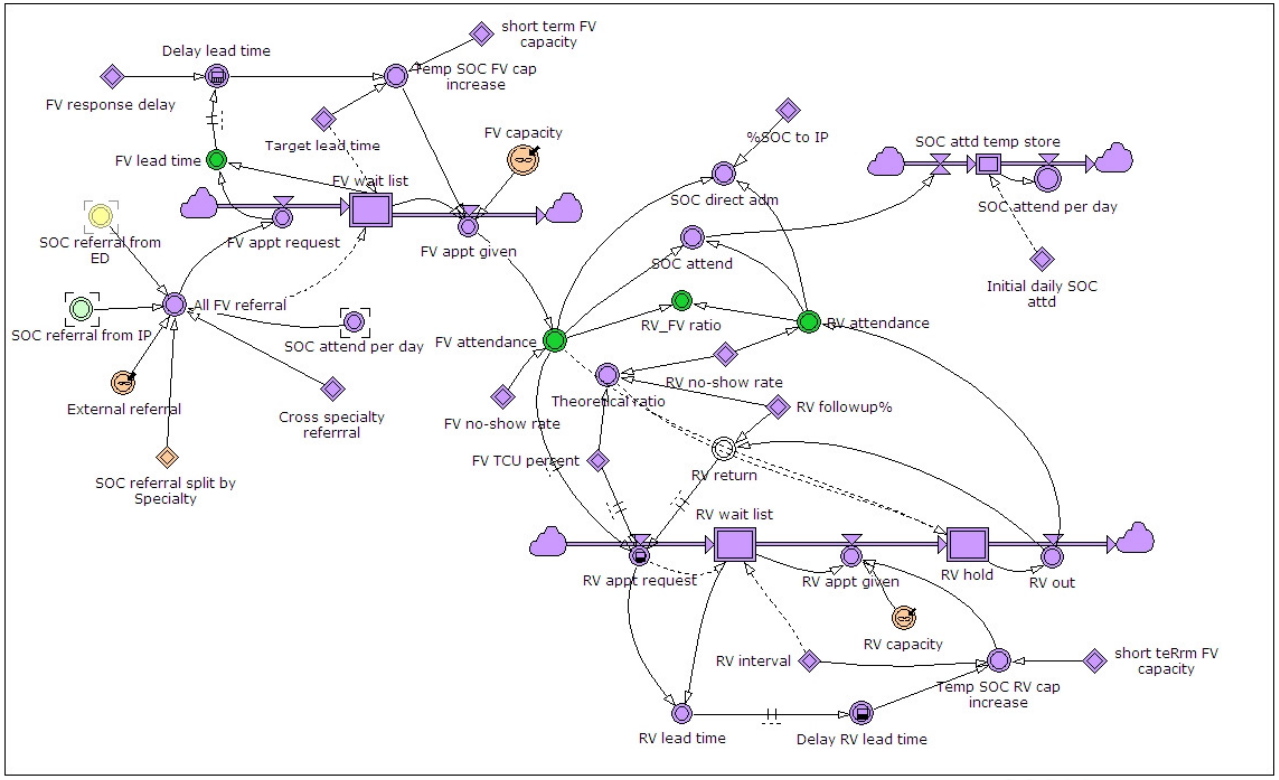


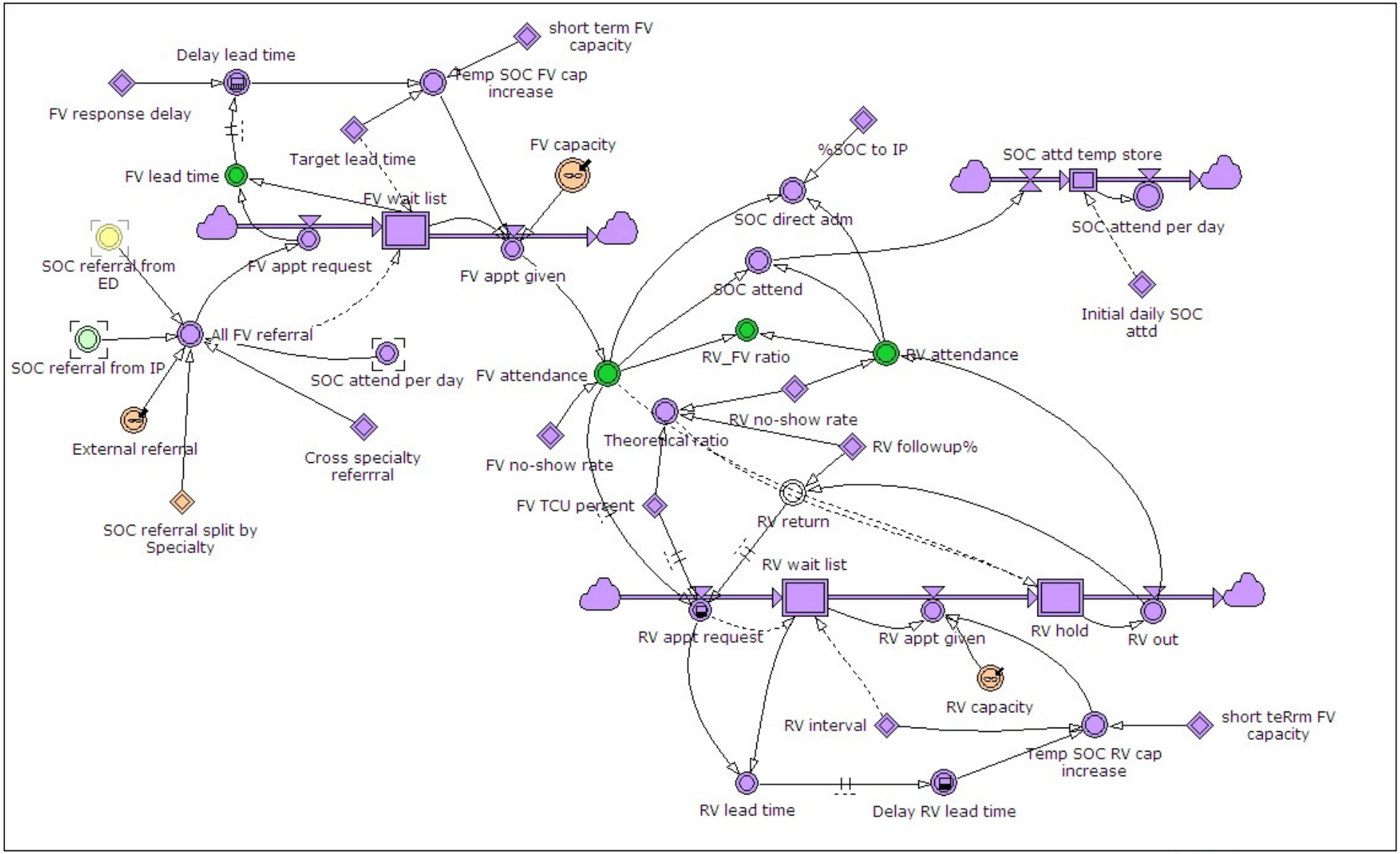

A&E | Ward

OT | SOC



# SOC patient flow (with feedback)



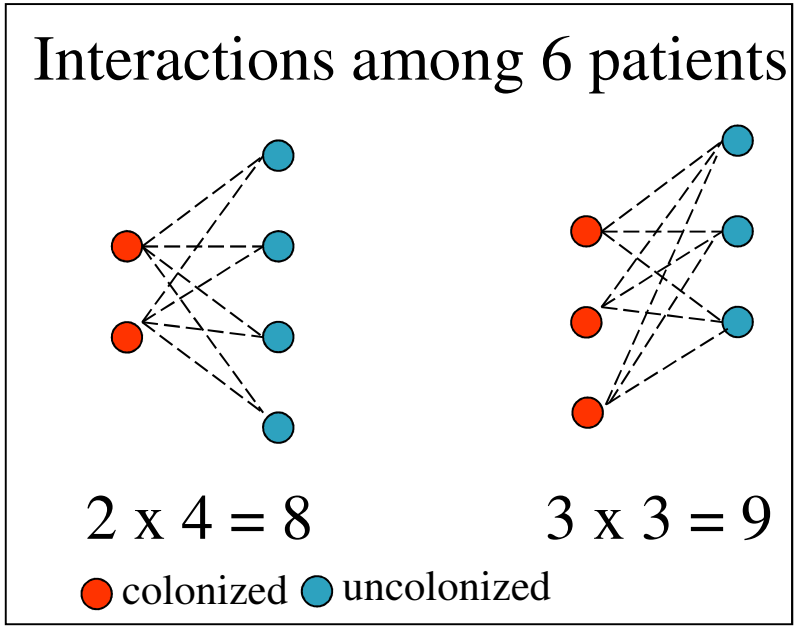
# Infectious disease transmission

- In 2011 at TTSH, to lower MRSA infections we considered whether to
  - Stick to culturing clinically indicated cases with 2 day delay (and therefore exposure) OR
  - Universal screening of nearly all patients at ED using more expensive PCR (2 hours) and cohort directly
- A cost effectiveness/savings analysis

# What's the intuition behind SIR model?
# Susceptibility-Infectious-Recovery



The transmission rate is hypothesized to be proportional to the possible no of interactions. This is the product of the colonized and uncolonized patients.




| Infected<br>I | Not infected<br>N–I | Interactions<br>I *(N–I) | Remarks |
|---|---|---|---|
| 0 | 6 | 0 | No transmission |
| 1 | 5 | 5 | |
| 2 | 4 | 8 | |
| 3 | 3 | 9 | Peak |
| 4 | 2 | 8 | |
| 5 | 1 | 5 | |
| 6 | 0 | 0 | No transmission |

Table – Transmission rate among 6 patients with different colonized proportions.

Transmission rate is not a constant during exposure and depends on the proportion of colonized patients at a time. All are colonized given sufficient exposure.

# Transmission model – a non-linear differential equation

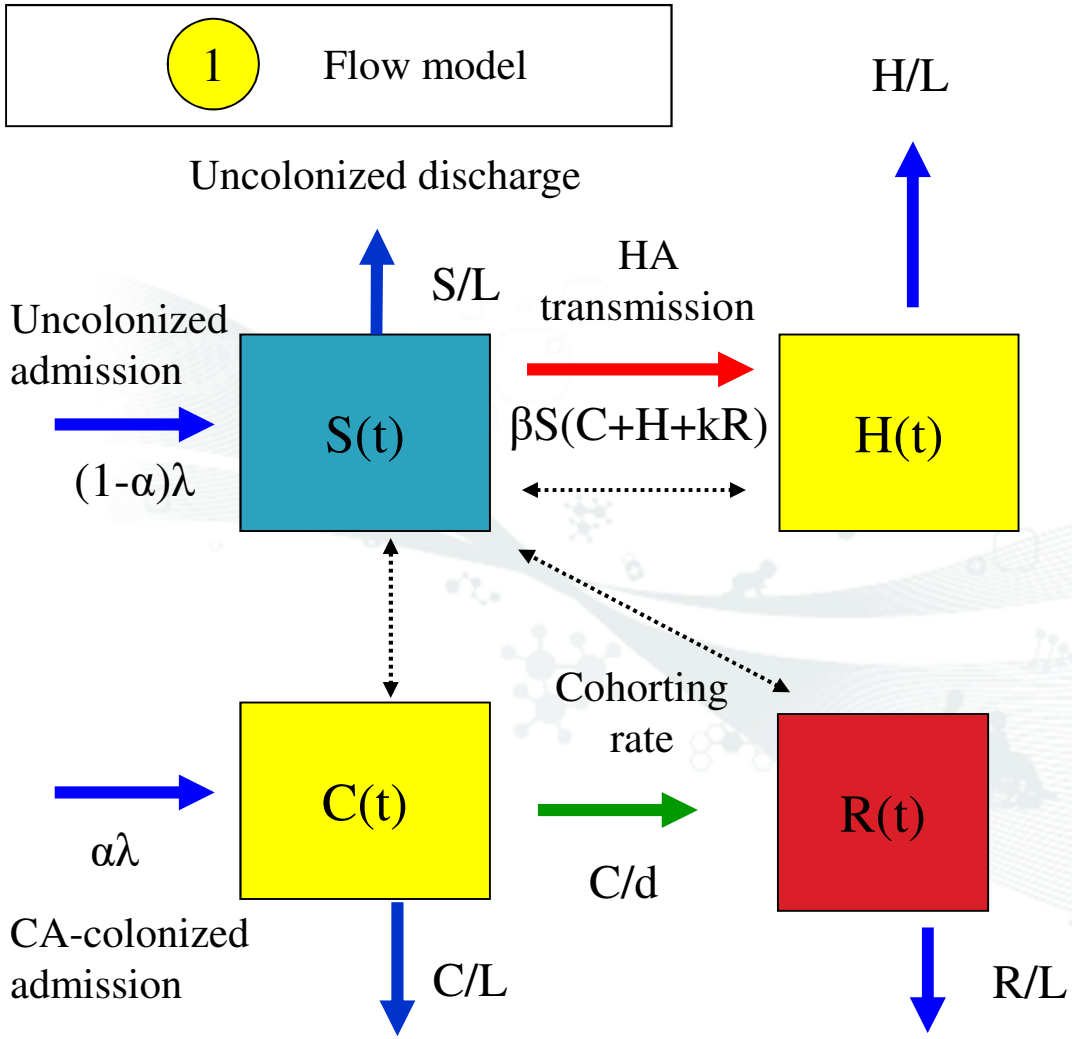


Transmission rate = constant X colonized patients X uncolonized patients

$$\frac{dI}{dt} = \beta * I(t) * [N - I(t)]$$

| Symbol | Description | Units |
|---|---|---|
| dI/dt | Transmission rate (incidence) | Patients/day |
| β | Transmission coefficient | /'000 patient-day |
| I(t) | Colonized patients at time t | Patients |
| N | Total no of patients | Patients |
| S(t)= N-I(t) | Uncolonized patients at time t | Patients |

# Colonization transmission model




2 Rate of change of S,I,R

$$\frac{dS}{dt} = (1-\alpha)\lambda - \beta S(C+H+kR) - \frac{S}{L}$$

$$\frac{dH}{dt} = \beta S(C+H+kR) - \frac{H}{L}$$

$$\frac{dC}{dt} = \alpha\lambda - \frac{C}{d} - \frac{C}{L}$$

$$\frac{dR}{dt} = \frac{C}{d} - \frac{R}{L}$$

3 At steady state there is no change

Set d()/dt = 0 and solve the set of equations to find S,H,C,R.

# *FORECASTING STEADY STATE PREVALENCE OF COVID-19 IN FOREIGN WORKER DORMITORIES AS OF 24 MAY 2020*

Palvannan R. K., Dr Aidan Lyanzhiang Tan, Teow Kiok Liang, Dr Heng Bee Hoon

## *HIGHLIGHTS*

- The steady state prevalence of past and new infections in foreign worker dormitories was forecasted by modelling data as of 24 May 2020, with results being reasonably close to publicly available data published by Ministry of Health, Singapore on 14 December 2020.
- Key modelling assumptions: a) There was a large pool of infected and infectious cases in foreign worker dormitories at the end of March 2020 when attention was turned to this setting; b) There were separate streams for symptomatic and asymptomatic patient pathways.

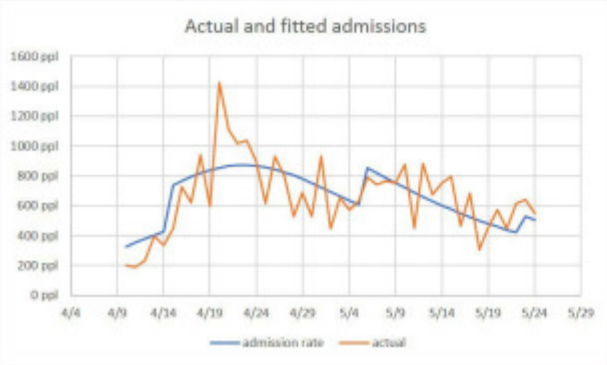
## INTRODUCTION

In Singapore, COVID-19 transmissions in the general community and foreign workers were reported separately, and even considered independent. Foreign worker dormitories (FWDs) collectively housed about 320,000 workers of foreign nationalities across multiple buildings of different layouts. In this article, we report a forecast of infections in FWDs using infectious disease transmission modelling and assumptions on baseline parameters.

## METHODS

A 2-flow (asymptomatic and symptomatic) Susceptible-Infectious-Recovered (SIR) model was built to baseline and forecast transmissions of COVID-19. The baseline historical transient incidences from April to May 2020 used to feed the model are shown in Figure 1. Baseline model parameters which were calibrated or based on assumptions from literature are described in Table 1. Transmission flows using Powersim Studio 6a®, a system dynamics modelling software, are shown in Figure 2. The model executes numerical deterministic simulations of a set of coupled non-linear ordinary differential equations. They assumed aggregate scope and complete mixing of infectious and susceptible populations in this study.

**Figure 1. Baseline historical transmissions**






COVID-19 PANDEMIC

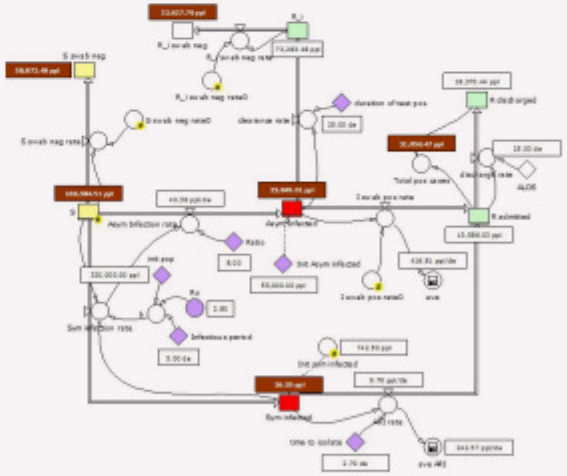
## RESULTS

The steady state model forecast was 45,000 PCR (new infections) cases and 106,000 seropositiv infections) cases, while Ministry of Health reported on 14 December 2020 that the actual case FWDs were 54,000 PCR cases and 98,000 seropositive cases. Results were similar for varying capacities of the FWDs.

**Table 1. Estimates of transmission parameters**

| PARAMETERS | VALUE | REM |
|---|---|---|
| POPULATION | 320,000 | FW Pop |
| BASIC REPRODUCTION NUMBER ($R_0$) | 2.6 | Assume nat |
| INITIAL ASYMPTOMATIC PATIENTS | 55,000 | Assume to reach based on $R_0$=4 from 20 Ap |
| INITIAL SYMPTOMATIC PATIENTS | 400 | Function of initial asymptomat |
| RATIO OF ASYMPTOMATIC : SYMPTOMATIC INFECTION RATES | 8:1 | Anecdotal assumption/cal |
| INFECTIOUS PERIOD | 5 Days | |
| TIME TO ISOLATE SYMPTOMATIC PATIENT | 2.5-3 Days | 2 days as pre-symptomatic, 1 day to |
| MEAN DURATION OF INFECTION IN ASYMPTOMATIC PATIENT | 25 Days | Patient will be PCR+ for |
| SWAB TEST CAPACITY | 1,000-3,000 Patients/Day | Ramped up from 10 A |
| AVERAGE LENGTH OF STAY (ALOS) IN COMMUNITY ISOLATION FACILITY | 25 Days | |

**Figure 2. SIR transmission model**



## CONCLUSION

A SIR model was built to forecast steady state prevalence of COVID-19 in FWDs that was rea close to actual numbers. While we do not rule out that the proximity of our results to the actu may be coincidental, the results suggest the potential validity of the model assumptions and ap adopted in this study.

# Glucose-Insulin IVGTT model

- A model of glucose dynamics, will it help in understanding abnormal patterns in a normal glycemic person?

$$\frac{dG(t)}{dt} = -b_1 G(t) - b_4 I(t) G(t) + b_7,$$

$$G(t) \equiv G_b \ \forall t \in [-b_5, 0), \qquad G(0) = G_b + b_0$$

$$\frac{dI(t)}{dt} = -b_2 I(t) + \frac{b_6}{b_5} \int_{t-b_5}^{t} G(s)\, ds, \qquad I(0) = I_b + b_3 b_0,$$

Mathematical modeling of intravenous glucose tolerance test, Gaetano AD, Arino O
Journal of mathematical biology (2000), 40: 136-168

# Leverages

## Physical parameters

Constants, parameters, numbers e.g. annual rate limits
The sizes of buffers and other stabilizing stocks, relative to their flows e.g. inventory size
The physical structure of material stocks and flows e.g. transport networks, population age structures.

## Feedback

The lengths of delays, relative to the rate of system change e.g. time to decision

The strength of negative feedback loops, relative to the impacts they are trying to correct against.
The gain around driving positive feedback loops.
The structure of information flows e.g. who does and does not have access to information

More leverage

## Redesign

The rules of the system e.g. incentives, punishments, constraints

The power to add, change, evolve, or self-organize system structure e.g. invest in greater diversity
The goals of the system e.g. profit, do good, dominance, elite hospital
The mindset or paradigm out of which the system e.g. reflect on what/who created current system.
The power to transcend paradigms

Source: http://donellameadows.org/

# Conclusions

A) To diagnose *Policy resistance* we used *ST/SD* which relates *feedback structures -> behavior*

B) We used tools

a) ST: qualitative (Causal Loop Diagram)

b) SD: quantitative (stock & flow with feedback)

C) Discussed levels in leverages.

# Tools and References

- References
  - Systems Thinking
    - The Fifth Discipline, The art and practice of the learning organization, Peter M. Senge, 1990
    - The System Archetypes, William Braun, 2002
  - System Dynamics
    - Business Dynamics: Systems Thinking and Modeling for a Complex World, John Sterman, 2000
    - http://www.public.asu.edu/~kirkwood/sysdyn/SDRes.htm, System Dynamics Resource Page hosted by Craig W. Kirkwood
  - MIT System Dynamics Group, http://web.mit.edu/sdg/www/

- Software tools
  - Powersim®