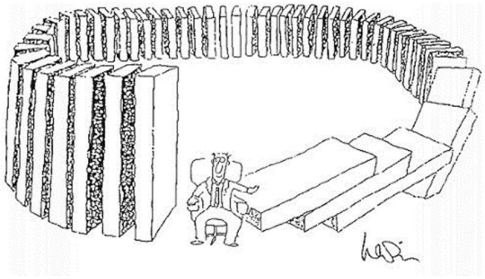
SYSTEMS THINKING & SYSTEM DYNAMICS



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HSOR@NHG
The evidence behind your decisions

Preamble (+/-)

1. Weeds are doubling themselves every day in a pond, the size of a football field. On the 20th day, the pond is full.

Q1. When is the pond ¼ full?

Q2. What do you see <u>halfway</u> on the 10th day?

2. Room temperature is 30 degrees. You set the air conditioner to 25 degrees.

Q1. What will be the temperature in 1 min, 5 min?

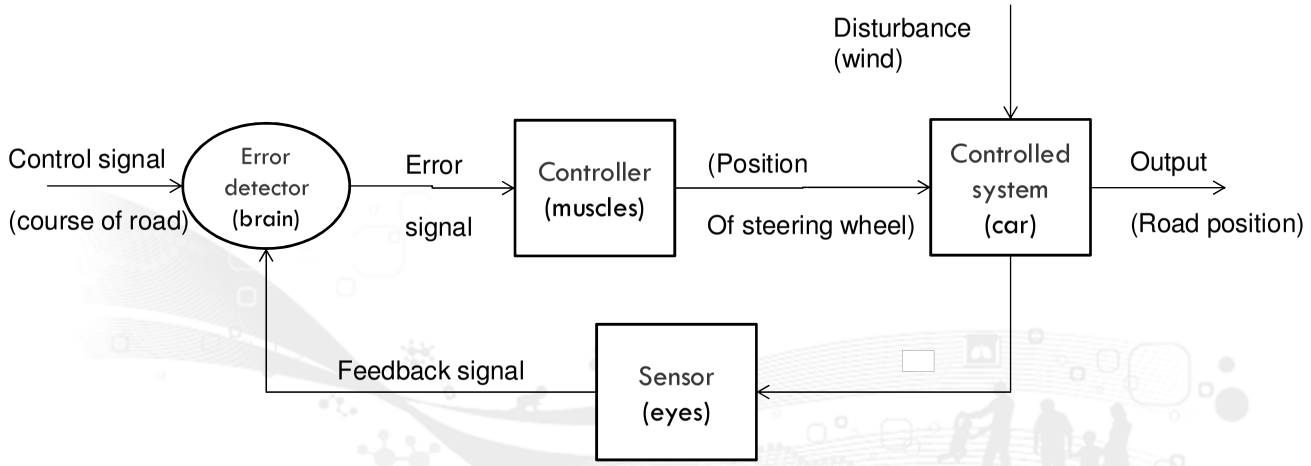
Systems Sciences

- A system has components but the relationships among them can create complex overall behavior.
  - Top down analysis by decomposition is not revealing.
- How the structure determines the function or behavior is explained by Systems Thinking/Dynamics.

Systems Thinking and Dynamics

- The central concept is that a system's dynamic behavior is caused by feedback structures.
- To absorb environmental shocks (e.g. demand) the system is self-stabilizing (dominated by negative feedback) and may have some reinforcing behavior (positive feedback) with self limiting checks.
- Feedback structures are found in Natural, Engineering and Organizational systems.
- ST/SD can provide definitions, visual tools, dynamic maths models, archetypes & cross examples.

Feedback control

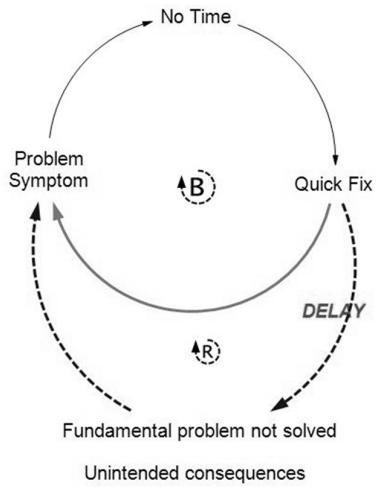


Houk J, Henneman E: Feedback control of muscle: introductory concepts. In Mountcastle VB [ed]: *Medical Physiology, 13th ed., Vol. 1*. St. Louis, Mosby, 1974

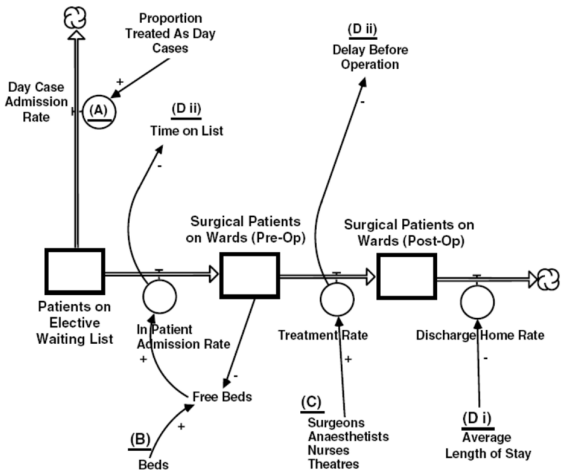
Examples

Systems	Control		Adaptation
	Negative feedback	Positive feedback	
Health	Homeostasis	Delivery contractions Early epidemic	Evolution
Engineering	Feedback control in automation	Signal amplification	Redesign
Organization	Capacity adjustment to meet small surges	Runaway problems	Renewal

Systems Thinking (qualitative)



System Dynamics (quantitative)



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

Policy resistance

- *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.
- High variability in patient admission/LOS in inpatient departments, leads to overflow. This may prompt ring-fencing of beds by some specialties which increases the variability, prompting further ring-fencing.
- The inability to change patient behavior despite poor health is a strong negative feedback to stick to old habits.

Use what you learn to …

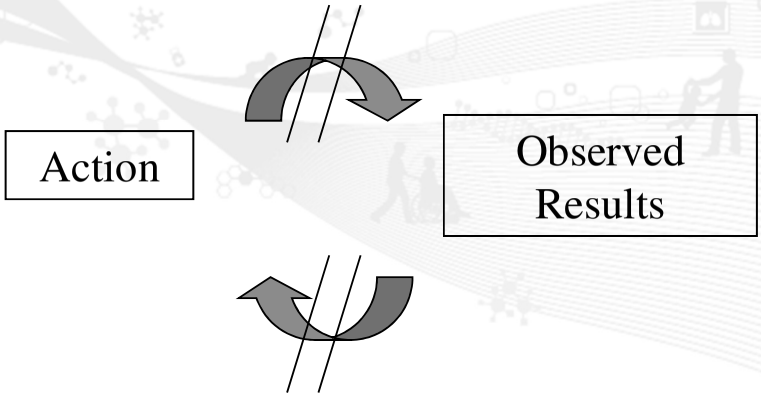
- *Understand*
  + why self stabilizing systems behave the way they do under shocks, in the short and long term.
- *Share*
  + your understanding of a causal model of a system with feedback structure.
- *Judge*
  + if we can improve the current intervention cost effectively. If not, accept it.

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)

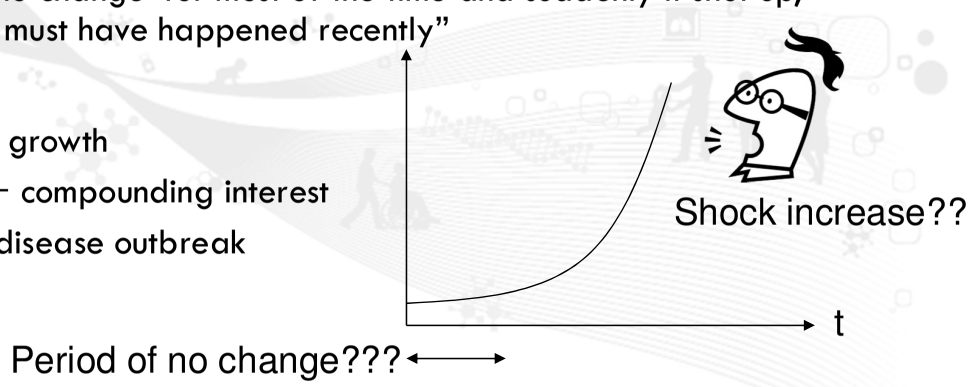
Concept 2 – Delays

- Delays in taking control action results in over and under correction (oscillations)
- Lag effect is due to delay in monitoring, not deciding, wait and see approach



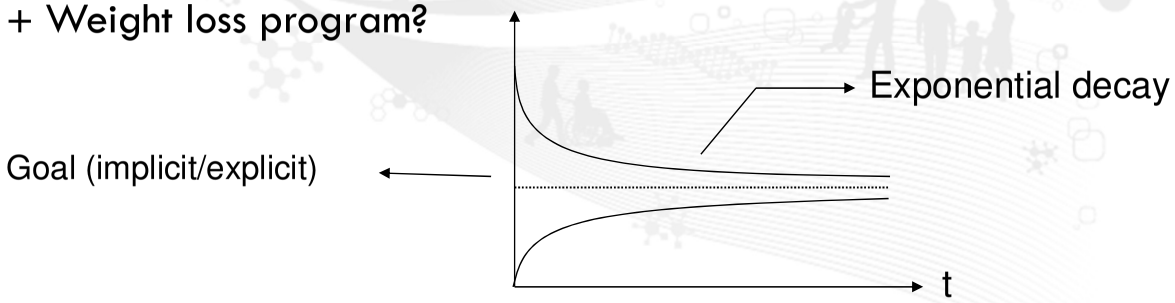
1. Exponential growth

- Key points
  - Caused by positive feedback
  - Can be growth or decline
- Identifiers
  - System reinforces itself, feeding onto itself, exponential growth, virtuous cycle, viscous 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. Goal seeking

- 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
  + Weight loss program?

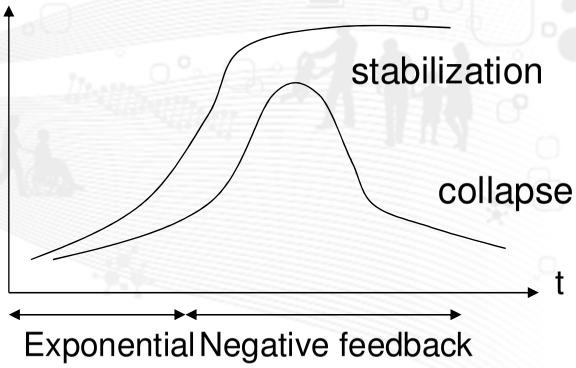


3. Oscillation

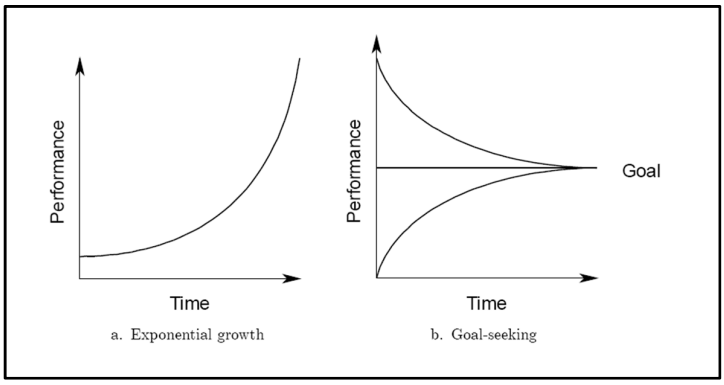
- Key points
  + Caused by negative feedback loops with time delays
  + What are sources of time delay
    - In initiating corrective action after seeing gap between goal & state
      - It takes time to measure and report information
    - Between corrective action and effect on state of system
  + Delay causes corrective action to overshoot goal, reverse and undershoot
  + can remain as cycles, die down or inflate depending on
    - Strength of loop/time delay
- Identifiers
  + Significant delays in a corrective process

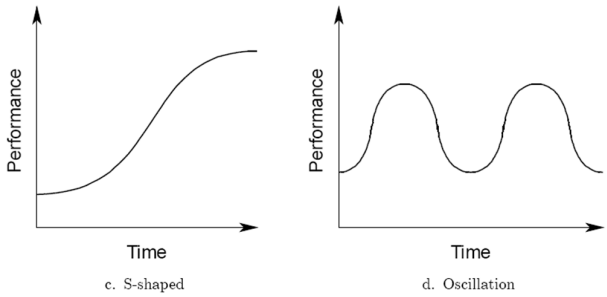
4. S-shaped growth

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



Fundamental dynamic patterns of system behaviour and the maths is differential equations





Exponential growth (+ve feedback)

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

Goal-seeking (-ve feedback)

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

Oscillation

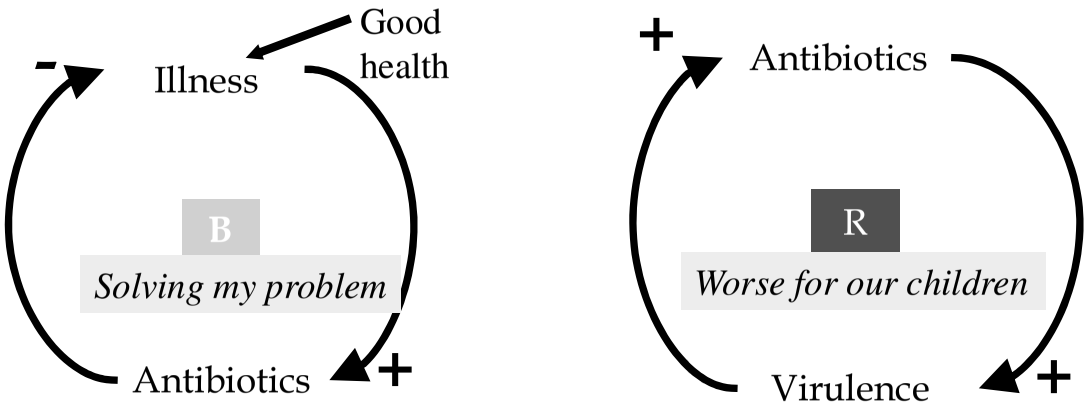
$$\frac{dx(t)}{dt} = T\arg et - x(t - Delay)$$

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

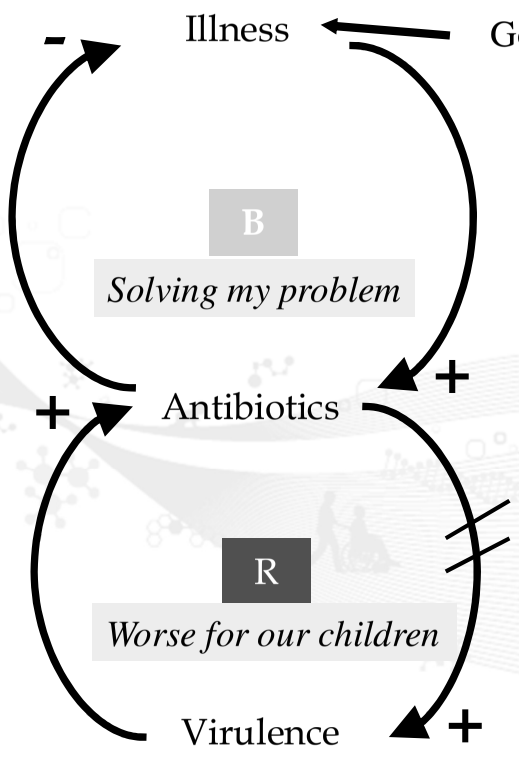
"R" means reinforcing; i.e., the causal relationships within the loop create exponential growth or collapse

"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.

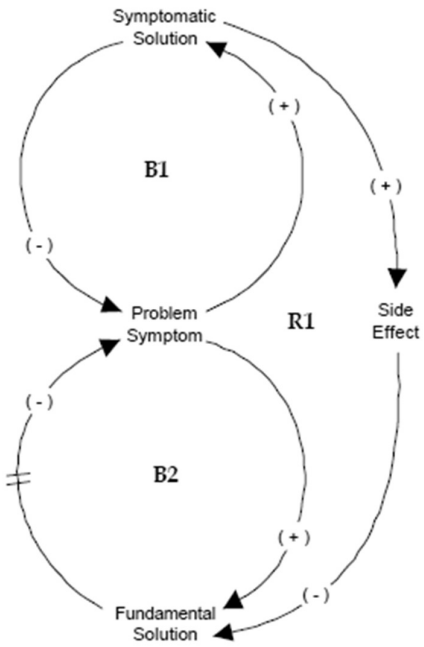
System Archetypes[1]

- 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

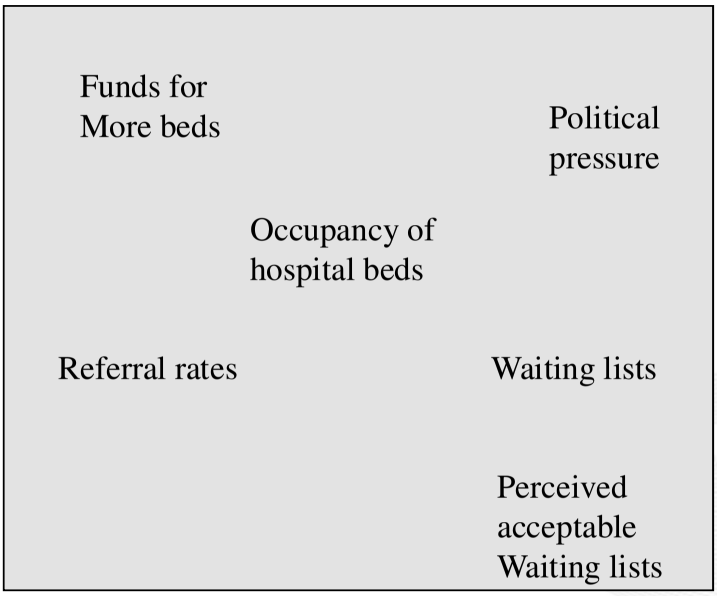
A convenient pill to shift the burden



Generic Archetype

- Putting out the fire (Problem Symptom)
- on the haze works annually (Symptomatic Solution).
- Its cheaper than penalizing the big producers (Fundamental Solution)
- It reduces the incentive to work on the painful fundamental problem (Side Effect).
- So it will come again.

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



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

<u>Exercise</u>

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

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

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			
SOC patients			

Understanding stock and flow (1)

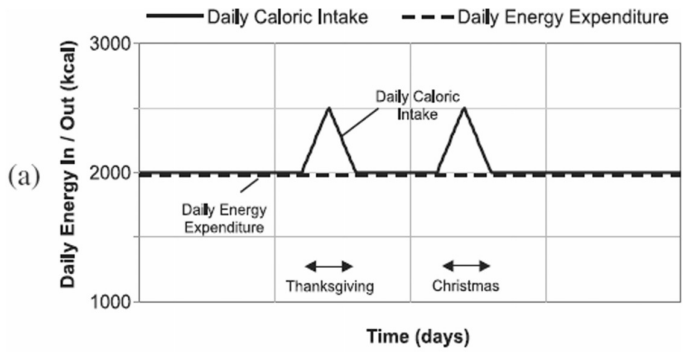
- Everyday 2 patients are admitted for a case of outbreak. Their average stay in a special unit of care is 3 days.

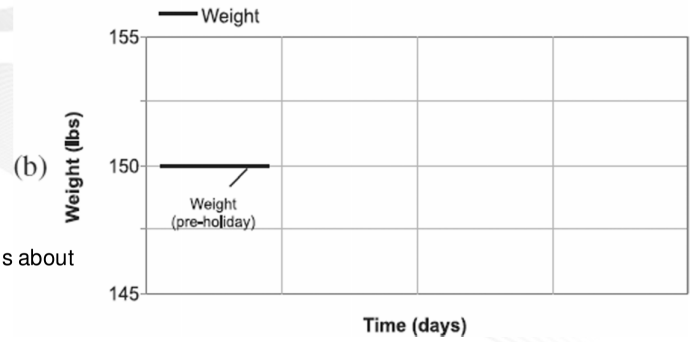
  a. How many beds are needed if the 'constant' epidemic lasted <u>for 8 days</u>?

  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

Flow rates – constant and variable

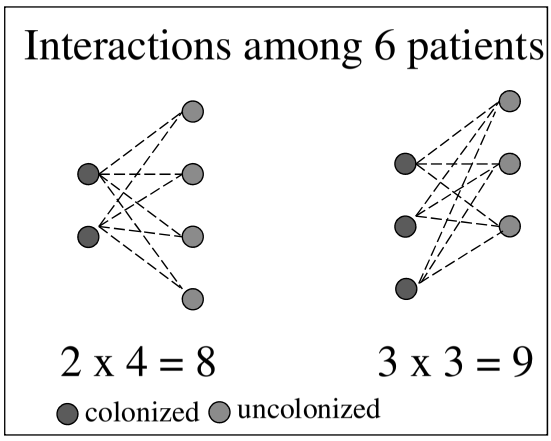
- The flow rates were independent. What if they are not?
- That is there is feedback to the flow from the stock level.

Examples

- Infectious disease transmission (mathematical epidemiology).
- Demand and supply simulation using Powersim®.
- Hospital dynamics.

What's the intuition behind SIR model?

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 I	Not infected N–I	Interactions 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

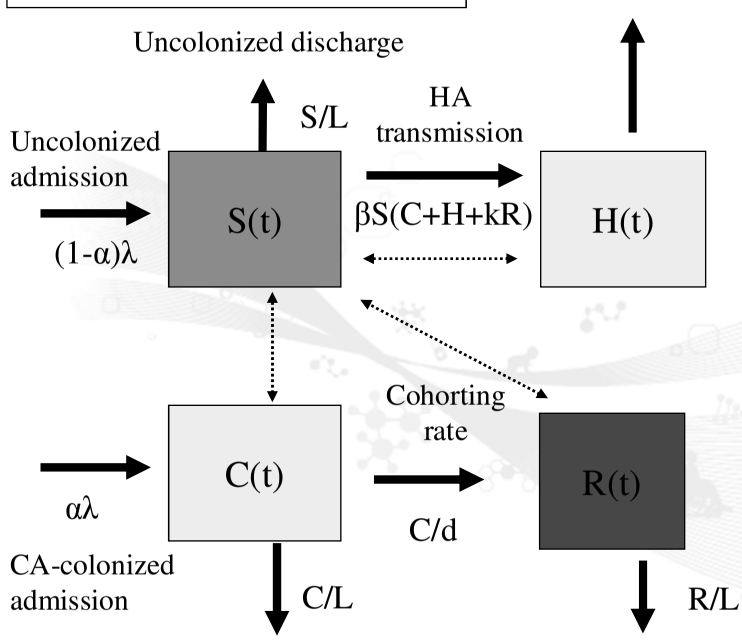
Transmission rate = constant X colonized patients X uncolonized patients

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

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

1 Flow 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.

Attributes of set of equations

- **Simultaneous:** there are 4 equations (because there are 4 stocks) to be solved
- **Differential equations:** because we are interested in the change in S, I and R over time
- **Ordinary:** there is 1 independent variable, t
- **First order:** dS/dt not d^2S/dt^2
- **Non-linear:** the transmission model is a product of dependent variables (S and I) (**see red**)

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

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

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

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

We solve these equations either analytically or computationally. The solution has a transient and steady state stages.

Patient flow model with cohorting[1]

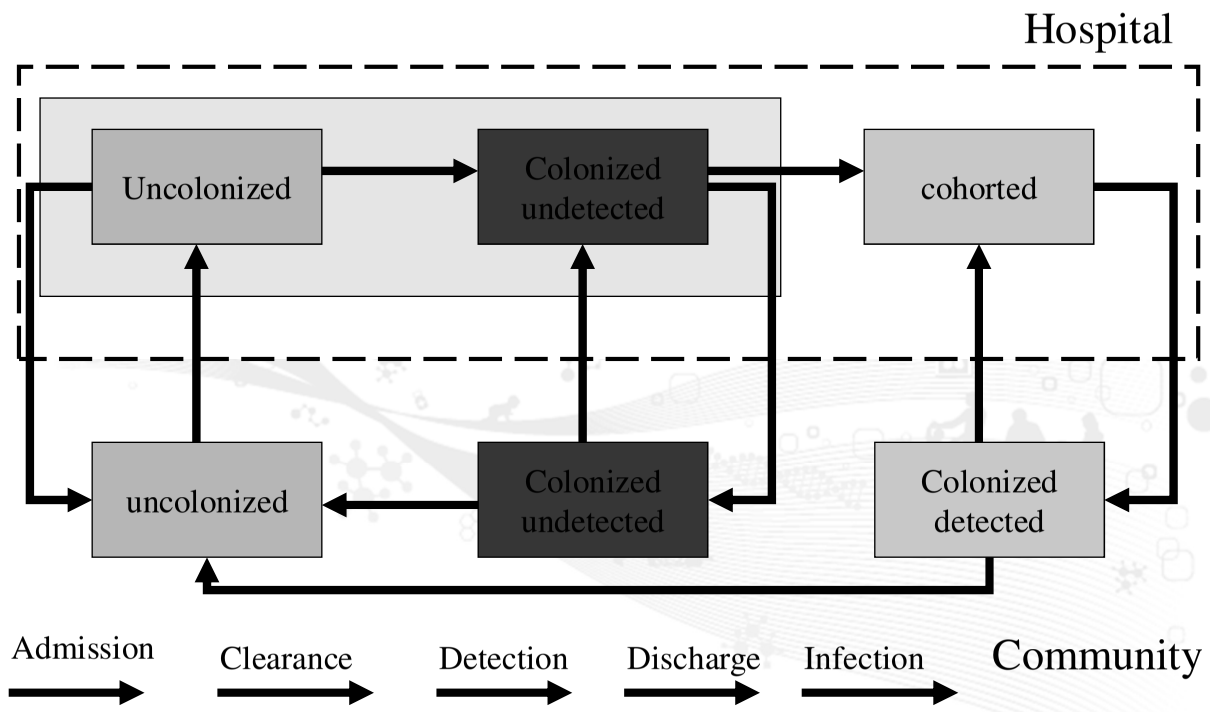
- What is the short and long term impact of MRSA cohorting?

- Assumptions
  - Colonized undetected patients may infect clean patients until test results are known
  - When detected they are isolated and labelled and therefore known upon readmission
  - Patients do not infect in the community

- Models
  - (Patient) Flow model, Maths model, Simulation model

1 - Modeling of transmission dynamics & economics of control of MRSA by patient isolation, Health Technology Assessment 2003, V7, No 39, Chapter 5, B S Cooper et. al.

Flow model



Maths model

$$\frac{dy}{dt} = \beta xy - dy + \mu_H y_c + \mu_L y'_c - \mu y - \Phi(y, z)$$

$$\frac{dx}{dt} = -\beta xy + dy + \mu_H x_c + \mu_L x'_c$$

$$\frac{dz}{dt} = \Phi(y, z) - \mu_i z$$

$$\frac{dy_c}{dt} = \mu y + \mu_i(1 - \pi)z - (\mu_H + d + \gamma)y_c$$

$$\frac{dx_c}{dt} = \mu x + dy_c + \mu_i \pi z - (\mu_H + \gamma)x_c$$

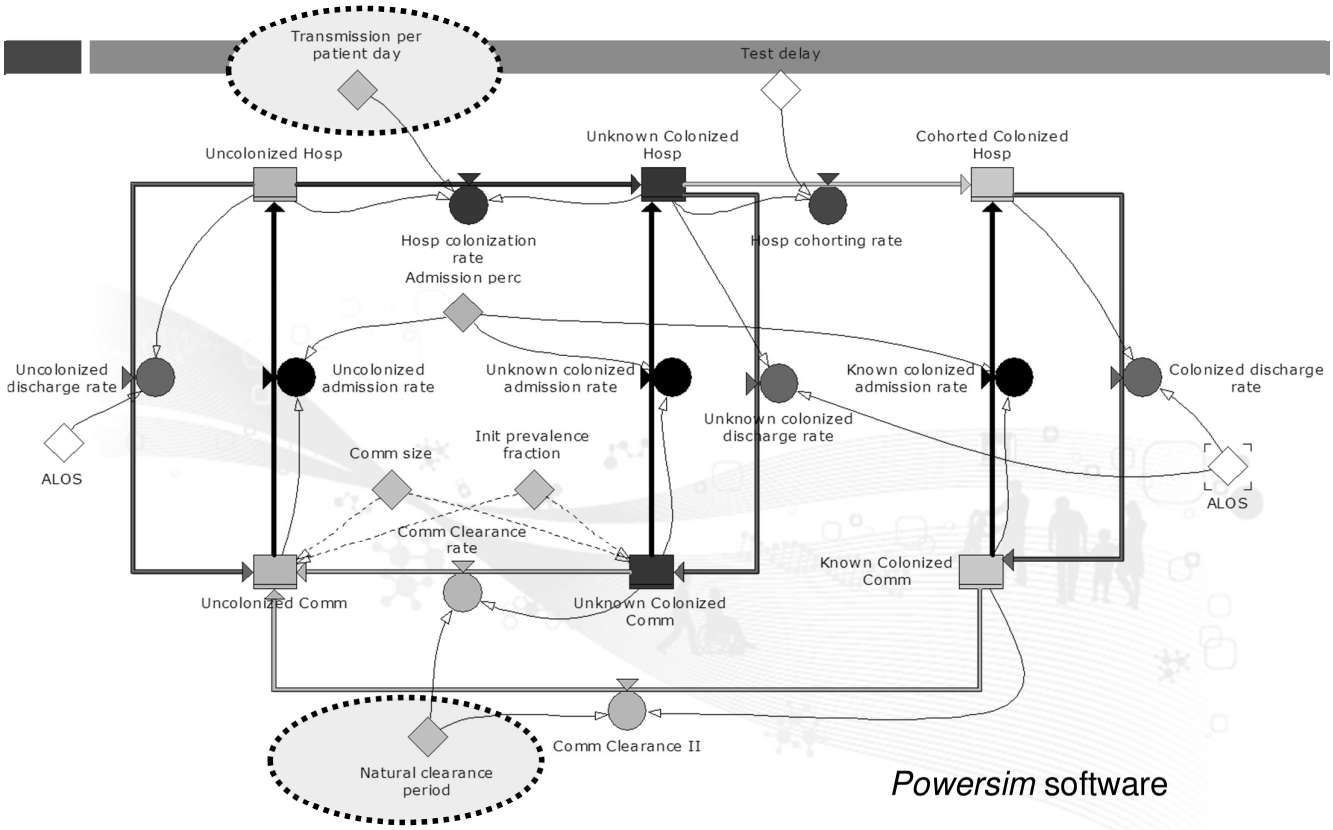
$$\frac{dy'_c}{dt} = \gamma y_c - (\mu_L + d)y'_c$$

$$\frac{dx'_c}{dt} = \gamma x_c + dy'_c - (\mu_L + d)x'_c$$

Equations do not show the Stock and flow relations or Information feedback. Visual modelling is preferred

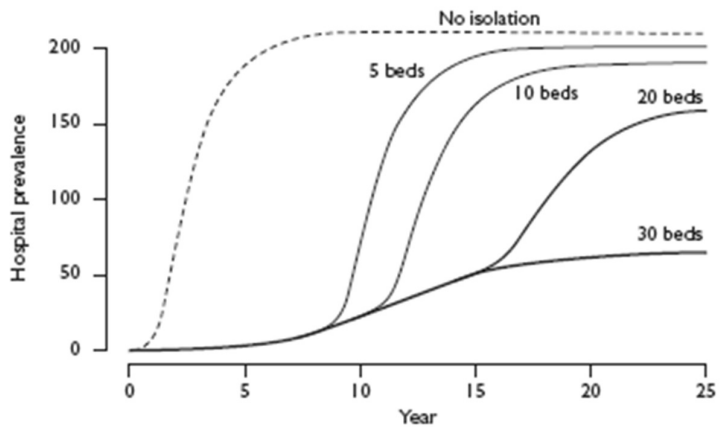
y	infected or colonised patients in the hospital
x	uninfected and uncolonised patients in hospital
x_c	uninfected and uncolonised patients in community with high admission rate
y_c	infected or colonised patients in community with high admission rate
x'_c	uninfected and uncolonised patients in community with low admission rate
y'_c	infected or colonised patients in community with low admission rate.

Simulation model



Powersim software

Results - Impact of size of cohorting



1. Cohorting is effective but it takes a long time to reduce prevalence
2. Until about the 8th year, there is no difference, due to more beds
3. After that we see significant improvement in both delaying and reduction of steady state hospital prevalence

Conclusions

- Concept

  + System's feedback structures (+/-) defines its dynamic behavior.

  + Application: analysis of policy resistance

- Qualitative (Systems Thinking)

  + Visual modeling tools (CLD) used to map feedback structures.

  + System archetypes are building blocks and known patterns.

- Quantitative (System Dynamics)

  + Stock and flow understanding is essential.

  + Feedback structures are modeled by differential equations.

  + Modeling software exists for study.

Exercise – developing a CLD

- Identify a persistent issue close to your work. It may have a pattern of behaviour we saw earlier or be a policy resistance.
- Develop a CLD
  - Think of the short term solutions and identify the causal factors, effects, outcome
  - Think of long term consequences of the solutions
  - Develop the feedback structure and delays. Indicate the p feedback type as balancing or reinforcing
  - Name your CLD
- Analyze the CLD to gain insights.
  - Are there leverage factors?
- Present your CLD for discussion

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

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®

REFERENCE

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The evidence behind your decisions

Weeds and positive feedback

- Exponential growth process? Every weed gives birth to 2 weeds.
- Assumed weeds lived longer than 20 days. Otherwise death rate must be considered.
- No of weeds = 2^{day} and not proportional to time. 'Sudden increase'? The only constant was 'doubling time' = 1 day.
- We can call this a *positive feedback* system. The rate of growth can easily surprise us even for a single variable i.e. the study of weeds only. Realistically there are 2 other variables: nutrients & threat.