Northeastern University

Multi-Scale Computational Modeling of Individuals' Behaviors : Digital Twins
Intensive Longitudinal Health Behavior Network (ILHBN)

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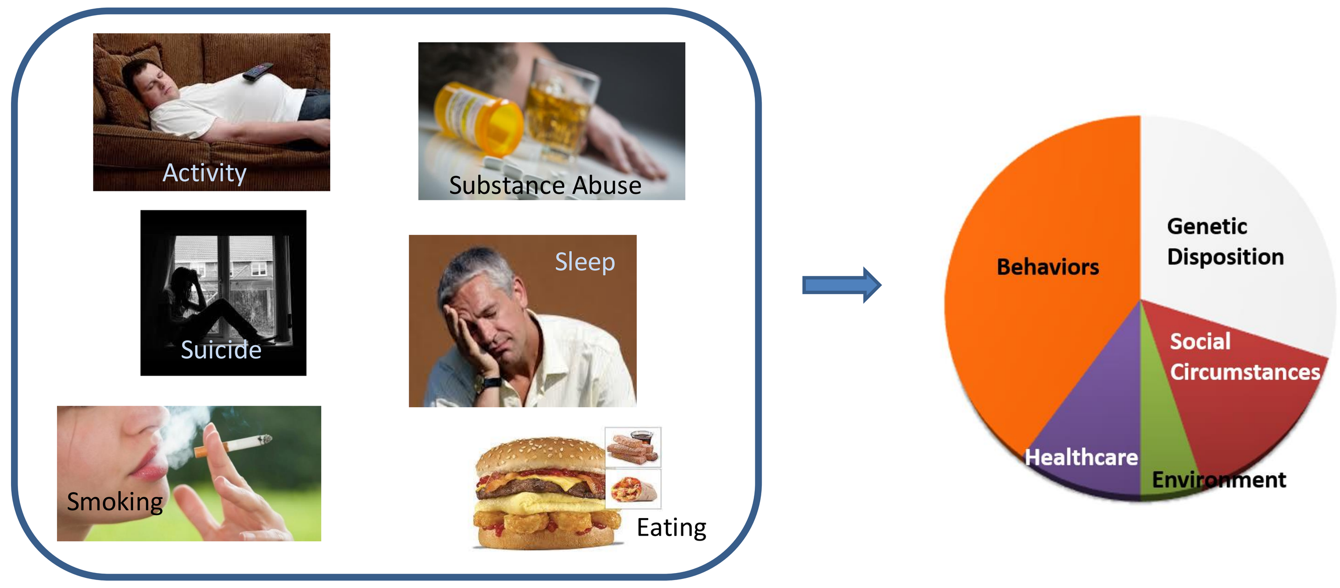
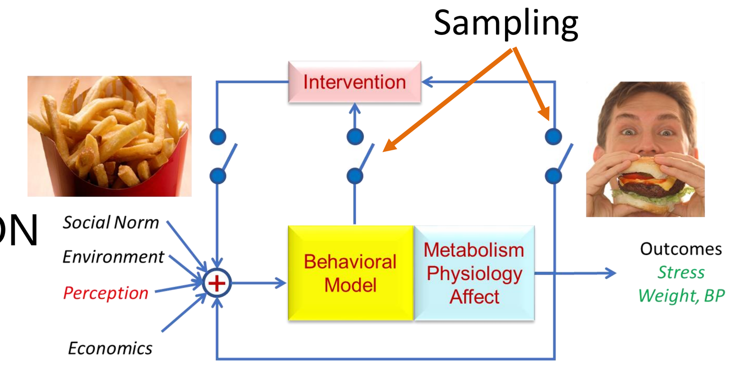
Health Behavior Modeling

Why behaviors? Poor health behaviors are destroying us and our economy



Improving behaviors requires closing the loop & PREDICTION



Closed Loop Involves:

- Unobtrusive measurements
- Measurement models
- Predictive computational models

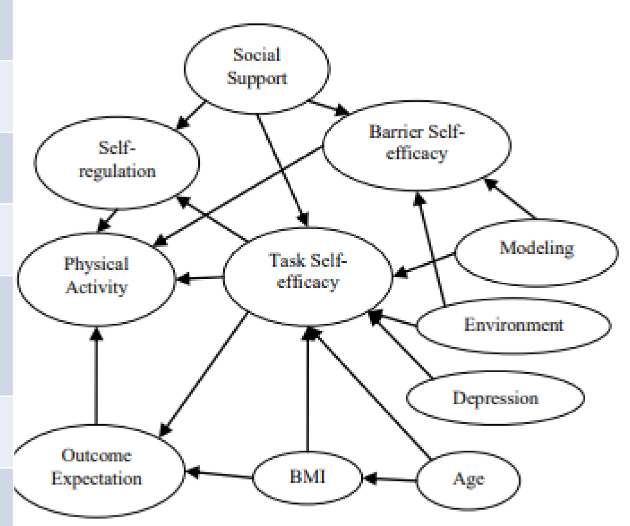
Computational Models = Digital Twins

Starting Point: Psychological Theoretical Framework
Structural Equations Models (SEM)

Example: Representation of Social-Cognitive Theory (SCT)

Examples of Variables

Variable	Measure
Social Support	Questionnaire
Internal Cues	Questionnaire
Perceived Barriers	Questionnaire
Self-Efficacy	Questionnaire
Outcome Expectancy	Questionnaire
Outcomes	Weight, BMI
Cue to Action	Questionnaire
Number of steps	Questionnaire
Activity Intensity	Accelerometry
Heart Rate	PPG



Acknowledgements

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Hybrid Dynamical Model

In general an SEM takes the form of $\eta = \Phi\eta + \Gamma\zeta$

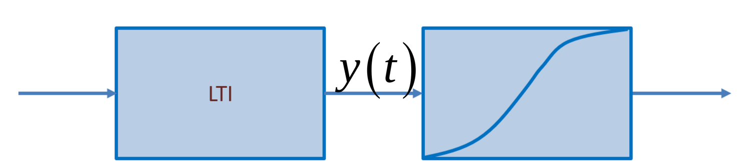
- where η is a vector of observable variables ζ is a vector of latent variables and Φ, Γ are real matrices. SEM can be assumed to be an approximation of a steady state of a dynamical system.
- If the correlations can be assumed to represent linear relationships among the state and output variables, the SEM can be used as a starting point to develop a linear, time-invariant (autonomous) state-space model

$$\frac{d\eta(t)}{dt} = \mathbf{A}\eta(t) + \mathbf{B}\zeta(t)$$

where ***A*** and ***B*** are matrices

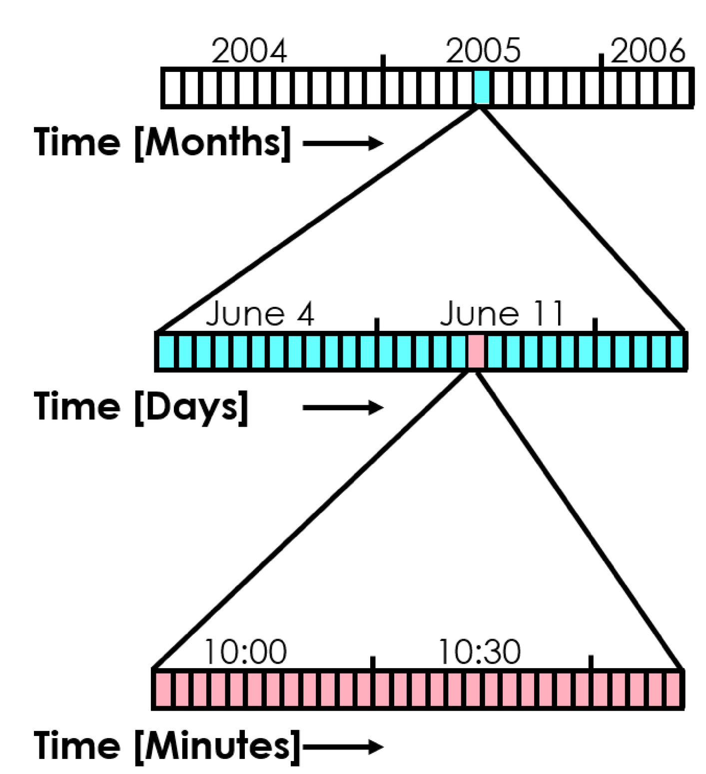
- **Modeling:** This type of dynamical state-space models of Social-Cognitive Theory and Theory of Planned Behaviors have been developed by a number researchers including Rivera, Martin, Chu, etc. (e.g. Martin et al. 2018).
- There are several shortcomings of current models that need to be addressed, for example:
  - **Multi-scale representation**: The different processes evolve over different time scales. For example, actions such as individual steps are in millisecond range, self-efficacy in in minutes and hours and depression-like state dependencies in weeks and months.
  - **Nonlinearities**: Although the dynamics of the system may be governed by a linear time invariant system, the process comprises several memoryless nonlinear components. A simple example of a hybrid dynamical system can be represented in terms of dynamical logistic regression

$$y(t) = H\left[\mathbf{Q}(t), \mathbf{X}(t)\right] \qquad P\left[y(t)\right] = \frac{1}{1+e^{-y(t)}}$$



Multiple –Scales in Time and State-Space

• Type	Sampling [sec]
Movements:	
• Speech	0.000002
• Gait phases, hand moves	0.01
• Facial expression	0.01
• Actions	
• Steps	20
• Bites (eating)	20
• Puffs (smoking)	20
• Activity	
• Walking, running	200
• Hygiene	200
• Eating	200
• Smoking	200
• Internal States:	
• Attitude, Motivation	2000
• Depression	100000



What are the Constraints Imposed by a Model?

If a model can represent any data, then its structure does not necessarily reflect the underlying mechanisms. Examples of functional constraints:

$F: \mathbb{R} \to \mathbb{R}$

- Homogeneity $\quad F(\lambda x) = \lambda^{\alpha} F(x)$
- Additivity $\quad F(x+y) = F(x) + F(y)$
- Linearity
  - Additivity
  - First order homogeneity

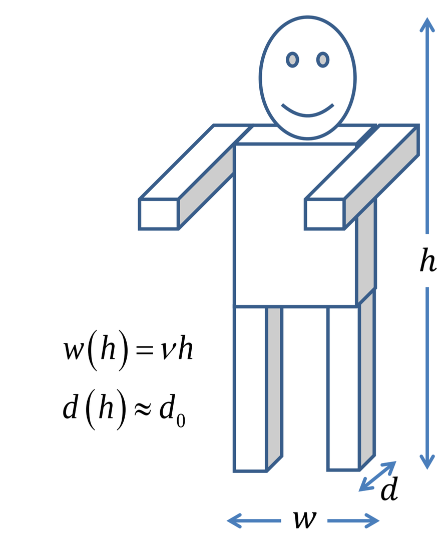
$$\begin{cases} F(x+y) = F(x) + F(y) \\ F(\lambda x) = \lambda F(x) \end{cases} \qquad \alpha, \lambda \in \mathbb{R} \quad \alpha > 0$$

- Zero-th order homogeneity: Scale Invariance

$$P(\lambda x, \lambda y) = P(x, y)$$

- Example: Body-Mass Index (BMI)

$$Q(\lambda^2 h, \lambda w) = Q(h, w)$$



System Identification: Mechanistic Models + Machine Learning

System identification is used to determine mechanistic model characteristics and parameters from empirical data. In that sense, system identification is a process of applying machine learning to models of dynamical systems (estimating parameter values).

The approach involves representing the dynamical system model by discrete difference equations and converting to a form of auto-regressive, moving average representation. Since the theoretical relationship among variables provided a structure for the dynamical system, we can use so-called "gray box" system identification techniques, see for example, Martin 2018 with a system represented by $\eta_{t+1} = G\eta_t + H\zeta_t$ derived from the continuous form of the state-space equations.

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