**About this tutorial**

- Goal is to discuss how engineering control theory can inform the design and implementation of time-varying adaptive preventive interventions.
- Talk will be focused on describing important concepts; it will not be a comprehensive survey.
- Emphasis will be given to **establishing connections** between prevention/behavioral health, methodology, and engineering, and the opportunities (and challenges) that these present to the behavioral scientist, the methodologist, and the engineer.
• K25DA021173*, “Control engineering approaches to adaptive interventions for fighting drug abuse,” Mentors: L.M. Collins (Penn State) and S.A. Murphy (Michigan).

• R21DA024266*, “Dynamical systems and related engineering approaches to improving behavioral interventions,” NIH Roadmap Initiative Award on Facilitating Interdisciplinary Research Via Methodological and Technological Innovation in the Behavioral and Social Sciences, with L.M. Collins, Penn State, co-PI.

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Some Similarities Between Prevention and Control Engineering

• Prevention scientists are interested in developing and delivering interventions that:
  - are strongly effective, with high levels of adherence.
  - display uniformity and reproducibility despite heterogeneity of the target population, and inherent variability associated with delivery of the intervention,
  - are cost-effective in nature.

  All these goals are compatible with the objectives of control systems engineering...

Some Differences...

• Mathematical skill sets are different; furthermore, methodological perspectives for viewing the world are different (statistical vs. input/output dynamical systems viewpoints).

• Terminology can be a barrier; we use many of the same terms to mean very different things.

• Prevention scientists naturally think in terms of populations; control engineers tend to think in terms of single participants.

• Experimental design in prevention settings encompasses a larger and broader set of considerations as compared to traditional engineering applications.
Basic Components of Adaptive Interventions
(Collins, Murphy, and Bierman, Prevention Science, 5, No. 3, 2004)

• The assignment of a particular dosage and/or type of treatment is based on the individual’s values on variables that are expected to moderate the effect of the treatment component; these are known as tailoring variables.

• In a time-varying adaptive intervention, the tailoring variable is assessed periodically, so the intervention is adjusted on an on-going basis.

• Decision rules translate current and previous values of tailoring variables into choice(s) of treatment and their appropriate dosage.

Adaptive Intervention Benefits
(Collins, Murphy, and Bierman, Prevention Science, 5, No. 3, 2004)

• An effective adaptive intervention strategy may result in the following advantages over fixed interventions:
  – Reduction of negative effects (i.e., stigma),
  – Reduction of inefficiency and waste,
  – Increased compliance,
  – Enhanced intervention potency.

• Adaptive interventions can serve as an aid for disseminating efficacious interventions in real-world settings.

Adaptive Intervention Simulation
(inspired by the Fast Track Program, Conduct Problems Prevention Research Group)

• A multi-year program designed to prevent conduct disorder in at-risk children.

• Frequency of home-based counseling visits assigned quarterly to families over a three-year period, based on an assessed level of parental functioning.

• Parental function (the tailoring variable) is used to determine the frequency of home visits (the intervention dosage) according to the following decision rules:
  - If parental function is “very poor” then the intervention dosage should correspond to weekly home visits,
  - If parental function is “poor” then the intervention dosage should correspond to bi-weekly home visits,
  - If parental function is “below threshold” then the intervention dosage should correspond to monthly home visits,
  - If parental function is “at threshold” then the intervention dosage should correspond to no home visits.

• The assigned dosage (frequency of counseling visits) decreases as the tailoring variable (parental function) increases, as prescribed by the decision rules.
Control Systems Engineering

The field that relies on dynamical models to develop mechanisms for adjusting system variables so that their behavior over time is transformed from undesirable to desirable.

• **Open-loop**: refers to system behavior without a controller or decision rules (i.e., MANUAL operation).

• **Closed-loop**: refers to system behavior once a controller or decision rule is implemented (i.e., AUTOmatic operation).

A well-tuned control system will effectively transfer variability from an expensive system resource to a less expensive one.

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Open-Loop (Manual) vs. Closed-Loop (Automatic) Control

• Climate control in automobiles is one of many illustrations of closed-loop control that can be found in daily life.

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The “Shower” Problem

**Controlled variables (y):**
- Temperature, water flow

**Manipulated Variables (u):**
- Hot and Cold Water Valve Positions

**Disturbances (d):**
- Inlet Water Flows, Temperatures

Objective: Adjust hot and cold water flows in response to changes in shower temperature and outlet flow caused by external factors.

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Control Systems Engineering

• Control systems engineering is a broadly-applicable field that spans all areas of engineering.

• Control engineering principles play an important part in many everyday life activities.

• Some examples of control system applications include:
  - Cruise control and climate control in automobiles
  - The “sensor reheat” feature in microwave ovens
  - Home heating and cooling
  - The insulin pump for Type-I diabetics
  - “Fly-by-wire” systems in high-performance aircraft
  - Many, many, more...
**Signal Definitions**

**Controlled Variables** \((y; \text{outcomes})\): system variables that we wish to keep at a reference value (or goal), also known as the setpoint \((r)\).

**Manipulated Variables** \((u)\): system variables whose adjustment influences the response of the controlled variable; their value is determined by the controller/decision policy.

**Disturbance Variables** \((d)\): system variables that influence the controlled variable response, but cannot be manipulated by the controller; disturbance changes are external to the system.

Both manipulated \((u)\) and disturbance \((d)\) variables can be viewed as independent \((x)\) variables; disturbances are exogenous, while manipulated variables can be adjusted by the user.

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**Control System Components**

**Sensors** (i.e., assessment instruments): devices needed to measure the controlled and (possibly) the disturbance variables.

**Actuators**: devices needed to achieve desired settings for the manipulated variables.

**Controllers** (i.e., clinical decision rules). These relate current and prior controlled variable, manipulated variable, and disturbance measurements to a current value for the manipulated variable.

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**Feedback Control Strategy**

- **In feedback control:**
  - the measured controlled variable \((y)\) is compared to a goal (also known as a reference setpoint \((r)\)),
  - a control error \(e = r - y\), representing the discrepancy between \(y\) and \(r\) is calculated.
  - a control algorithm determines a current value for the manipulated variable \((u)\) based on current and previous values of \(e\) and \(u\).
The “Magic” of Feedback
(Adapted from K. J. Åström’s “Challenges in Control Education” plenary talk at the 7th IFAC Symposium on Advances in Control Education, Madrid, Spain, June 21-23, 2006).

Feedback has some amazing properties:

• can create good systems from bad components,
• makes a system less sensitive to disturbances and component variations,
• can stabilize an unstable system,
• can create desired behavior, for example, linear behavior from nonlinear components.

Major drawback: it can cause instability if not properly tuned.

From Open-Loop Operation to Closed-Loop Control (Stochastic Viewpoint)

The transfer of variance from an expensive resource to a cheaper one is one of the major benefits of control systems engineering.
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Parental Function Dynamics
“Open Loop” Response

- Variations in intervention dose response for a single participant family

**Connecting ACE and Dynamical Systems Models (Fast Track Example)**

\[
ACE = E(Y_{i1}) - E(Y_{i0})
\]

\[
Y_{i1} = \sum_{t=1}^{N_{dur}} (PF_i(t-1) + K_{II} I(t - \theta|i) - D_i(t))
\]

\[
Y_{i0} = \sum_{t=1}^{N_{dur}} (PF_i(t-1) - D_i(t))
\]

\[
ACE = E \left( \sum_{t=1}^{N_{dur}} (K_{II} I(t - \theta|i)) \right)
\]

- Parental function change as a result of step changes in outflow (the disturbance variable) of varying magnitudes.

- Between-participant variability as a result of individual dynamic characteristics

Average Causal Effect (ACE) is a function of model parameters (gain, delay) and intervention dosages assigned during the course of the intervention.
Adaptive Intervention Using “IF-THEN” Rules

High Depletion ($D(t) = 5$)

Single participant family scenario. The goal is for the family to attain a 50% proficiency (dashed line) on a parental function scale at the conclusion of the three year intervention. Offset (where parental function fails to meet goal) is more pronounced when high depletion is present.

Multiple participant family simulation. The goal is for each family to attain a 50% proficiency (dashed line) on a parental function scale at the conclusion of the three year intervention. Offset is observed in all participant families.

Control Design Requirements

- Stability. Many different notions exist, but “BIBO” stability (bounded inputs resulting in bounded outputs) is usually sufficient.
- No offset. Control error $e = r - y$ should go to zero (meaning that the controlled variable should reach the goal) at a finite time.
- Minimal effect of disturbances on controlled variables.
- Rapid, smooth (i.e., non-oscillatory) responses of controlled variables to setpoint changes.
- Large variations (“moves”) in the manipulated variables should be avoided.
- Robustness, that is, performance should display little sensitivity to changes in operating conditions and model parameters.
Proportional-Integral-Derivative (PID) with Filter Controller Summary

\[ I(t) = I(t-1) + K_1 e(t) + K_2 e(t-1) + K_3 e(t-2) + K_4 (I(t-1) - I(t-2)) \]

Current Dosage = Previous Dosage
+ Scaled Corrections using Current and Prior Control Errors
+ Scaled Previous Dosage Change

- \( K_1, K_2, K_3, \) and \( K_4 \) are tuning constants in the controller;
- \( e(t) = (PF(t) - PF_{Goal}) \), where \( PF_{Goal} \) is the setpoint ("goal") and \( e(t) \) is the control error.
- The dosage decision \( I(t) \) is a continuous value between 0 and 100%, but for purposes of this example it is quantized into the nearest of the four dosage levels (1 weekly, 1 biweekly, 1 monthly, 0).

Controller/Decision Rule Comparison, High Depletion Rate (\( D(t) = 5 \))

"IF-THEN" rules

IMC-PID control (\( \lambda = 3 \); moderate speed)

36 month intervention reviewed at quarterly intervals. Offset problem is eliminated by more judicious assignment of intervention dosages during the course of the intervention.

Internal Model Control-Propportional Integral Derivative (IMC-PID) Controller Tuning Rules (Rivera et al., 1986)

User supplies open-loop model gain (\( K_0 \)), delay (\( \theta \)) and the adjustable parameter (\( \lambda \)); \( T \) is the review period

\[ I(t) = I(t-T) + K_1 e(t) + K_2 e(t-T) + K_3 e(t-2T) + K_4 (I(t-T) - I(t-2T)) \]

\[ \beta = \tau = \frac{\theta}{2} \]

\[ K_c = \frac{2(\beta + \lambda + \tau)}{\lambda (\lambda + \beta + \theta + \lambda + \tau + 1)} \]

\[ \tau_I = 2(\beta + \lambda + \tau) \]

\[ \tau_D = \frac{2(\beta + \lambda)}{2(\beta + \lambda + \tau + 1)} \]

\[ \tau_F = \frac{\beta \lambda^2}{2(\beta + \lambda + \lambda + \tau + 1)} \]

\[ K_1 = \frac{TK_c}{\tau_F + \tau} \left( 1 + \frac{T}{\tau_I} + \frac{T}{\tau_D} \right) \]

\[ K_2 = -\frac{TK_c}{\tau_F + \tau} \left( 1 + \frac{2\tau_I}{\tau_D} \right) \]

\[ K_3 = \frac{K_c \tau_D}{\tau_F + \tau} \]

\[ K_4 = \frac{\tau_F}{\tau_I + \tau} \]
The intervention dosage is adapted at quarterly intervals over a 36-month time period. The goal is for each family to attain a 50% proficiency (dashed line) on a parental function scale at the conclusion of the three year intervention.

**“IF-THEN” Decision Rules**

**Pros and Cons**

• PROS: Simple;
  – both measurement and dosage levels are categorical in nature.
  – decision rules are simple, compact, and easy to explain.

• CONS: Simplistic;
  – may not lead to desirable outcomes (e.g., offset, instability, and high degree of variability in response among participants may result).

**IMC-PID Controller**

**Pros and Cons**

• PROS:
  – reliance on model-based tuning results in improved outcomes (e.g., no offset, robust stability and performance).
  – continuous measurement of tailoring variables is naturally incorporated,
  – controller/decision policy remains compact; it includes an adjustable parameter ($\lambda$) defines a “speed of response.”

• CONS:
  – Model parameters ($K_i$ and $\theta$) need to be estimated prior to the intervention,
  – Adjustable parameter ($\lambda$) needs to be selected systematically (“tuning”),
  – Assigning continuous dosages to categories must be done with care,
  – Controller/decision rules harder to explain to non-experts.
Summary and Conclusions

- Behavioral interventions constitute uncertain, nonlinear dynamical systems, and can therefore benefit from a control engineering perspective.

- Applying a dynamical systems approach requires more frequent measurement and a recognition of the input/output nature of phenomena associated with behavioral interventions.

- A hypothetical adaptive intervention based on Fast Track has been simulated using a rule-based controller ("IF-THEN" decision rules) vs. engineering-based PID (Proportional-Integral-Derivative) decision algorithms.

- A fluid analogy, based on the principle of mass conservation, was useful in establishing a comparison between these various control systems.

- A plethora of opportunities exist in applying systems approaches to behavioral interventions which includes experimental design, development of optimal decision policies, and simulation.

Additional Topics (not covered)

- System identification: examines how to empirically obtain dynamical models from data; also enables simplifying other model types (e.g., system dynamics, agent-based models) into forms amenable for control.

- Feedforward control action: if disturbance variables can be measured, these can be incorporated as tailoring variables in the controller in a feedforward (i.e., anticipative) manner.

- Model predictive control*: control design paradigm that features advanced adaptive functionality such as constraint handling, decision-making involving multiple outcomes, and formal assignment of intervention dosages to discrete-valued categories.

*to be discussed during the session entitled, “Innovative Methodology for Adaptive Interventions Drawing from Engineering and Computer Science,” Grand Ballroom, Thursday, June 3rd, 1:15 - 2:45 p.m.

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Fluid Analogy for Mediation Analysis

Path Diagram:

\[ \tau_1 \frac{dM}{dt} = aT(t - \theta_1) - M(t) + e_1(t) \]

\[ \tau_2 \frac{dY}{dt} = c' T(t - \theta_2) + b M(t - \theta_3) - Y(t) + e_2(t) \]

Time constant (\( \tau \)) and delay (\( \theta \)) variables are essential features in this dynamic model representation for mediation.

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Fluid Analogy for the Theory of Planned Behavior*

*to be discussed during the session entitled, “Innovative Methodology for Adaptive Interventions Drawing from Engineering and Computer Science,” Grand Ballroom, Thursday, June 3rd, 1:15 - 2:45 p.m.

Any path diagram can be expressed into a corresponding fluid analogy described by a system of differential equations.
We have considered the importance of establishing connections between prevention/behavioral health, methodology, and engineering. Some implications of this work (not an exhaustive list):

- **Behavioral scientist**: willingness to collect and work with intensive longitudinal data, reconfigure interventions to enable adaptation (i.e., allow dosage changes through the course of the intervention).

- **Methodologist**: develop expertise and familiarity with differential equations, dynamical input/output system models, and control theory.

- **Control engineer**: work with data sets that may be irregularly sampled, have missing entries, and involve multiple human participants. Explore experimental designs meaningful to problems in behavioral health.

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**Additional References**

- Some additional tutorial presentations that may be of interest:

- A free web-based reference, written by two eminent control systems engineers: