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Seattle, WA
July 13 - 16, 2015

Model-Based Optimization of Learning Curves: Implications for Business and Government

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Outline

- Problem
- Opportunity
- Learning Curves
- Modeling Learning Curves
- Portfolio optimization
- Pilot Study
- Conclusion
- Way Ahead

Problem

- Major corporations spend substantial amounts annually on workforce training and development
- Don't have a way to quantify the Return On Investment (ROI) in terms of impact on learner time-to-proficiency and learning rate
- Also, learner deficiencies are not identified for targeted training
- As a result, companies resort to mass training – exorbitant cost, no guarantee of success

Opportunity

- Learning curves **describe** how:
  - repeated task performance results in decrease in task performance time
  - unit cost decreases as a function of units produced (experience curve)
  - time-to-proficiency decreases with accumulation of knowledge and skills (proficiency curve)
- Observation: learning curves can be **optimized** through optimal **allocation of funds and cohorts** to learning options and courses

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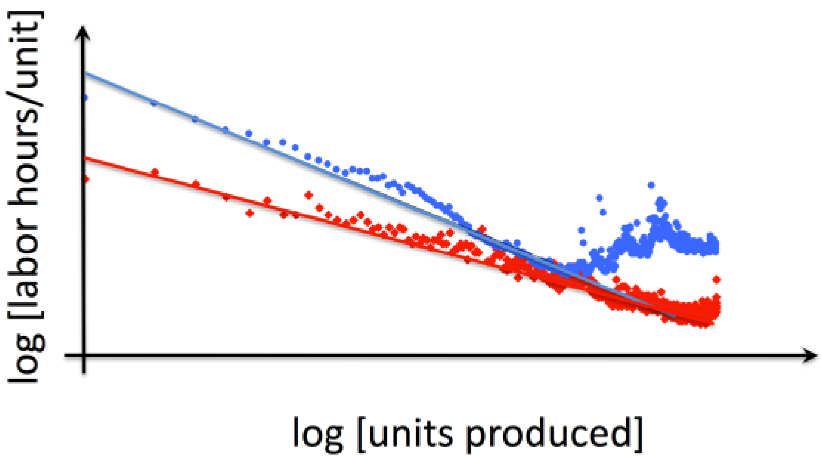
Learning Curves: Origin

- Recognized in the aircraft industry in 1936 (Theodore Paul Wright)
- **Key notion:** accumulating experience leads to improved proficiency and performance
- Boeing discovered that:
  - time to assemble an aircraft declined with increase in number of aircraft assembled
  - cost to assemble a new aircraft was highly predictable
  - rate of improvement (i.e. learning rate) was predictable could be characterized by a math formula
  - this meant that labor hours required for aircraft assembly could also be predicted with reasonable precision
  - phenomenon holds for a variety of manufacturing setups across industries (learning rates varied)
- Generalized by Bruce Henderson of BCG in the form of Power Law in 1968 ("experience curve")
  - experience curve effects: 10-25% in various industries

Learning Curves in Manufacturing: Aircraft industry Finding

- Increase in experience leads to improved performance
  - time to assemble an aircraft declines with # of aircraft assembled
  - each time a task is performed it takes less time than the time before - task duration decreases over time
  - reduction in time follows a predictable, repeatable pattern
  - cost to assemble new aircraft is predictable - math formula



1. *Model A (blue) shows initial faster learning 0.67 (solid blue line), while model B (red) has 0.39 (solid red line).*
2. *Late in the history of model A's production labor hours/unit increased sharply due to the reconfiguration of the original subsystem*

Exemplar Learning Curves

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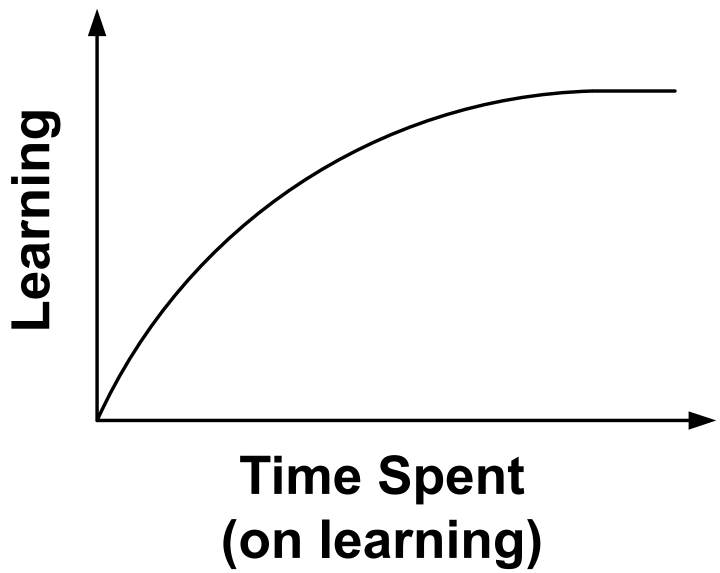
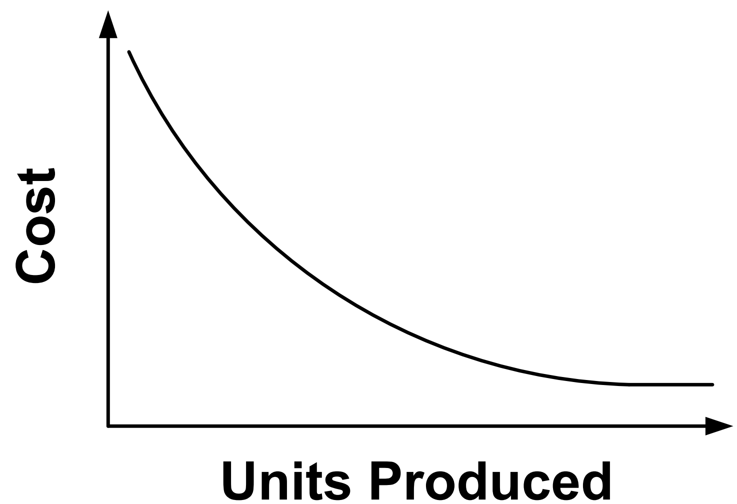
Proficiency Curve



Training Environment

Experience Curve



Production Environment

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Learning Curve: Implications

- Finding ways to accelerate learning can produce competitive advantage (e.g., starting production sooner than competitors)
- Strategies to improve learning rate invariably require **investment**
- Tradeoff between **investment (cost)** and **savings (benefit)** realized through increase in learning rate

Modeling and Analysis Framework

- Inputs and outputs
  - **Inputs:** budget, courses, learning options, learner pool (fixed)
  - **Output:** allocation of budget and cohorts to various learning options
- Types of **modeling and analyses**
  - **Investment optimization** - what-if budget allocation and learner allocation to learning strategies
  - **Sensitivity Analysis** - sensitivity of learning curves to changes in budget and learner allocation to learning options
  - **Comparative analysis** - compare different $ and cohort allocations in terms of time-to-proficiency, organizational metrics

Modeling Approaches

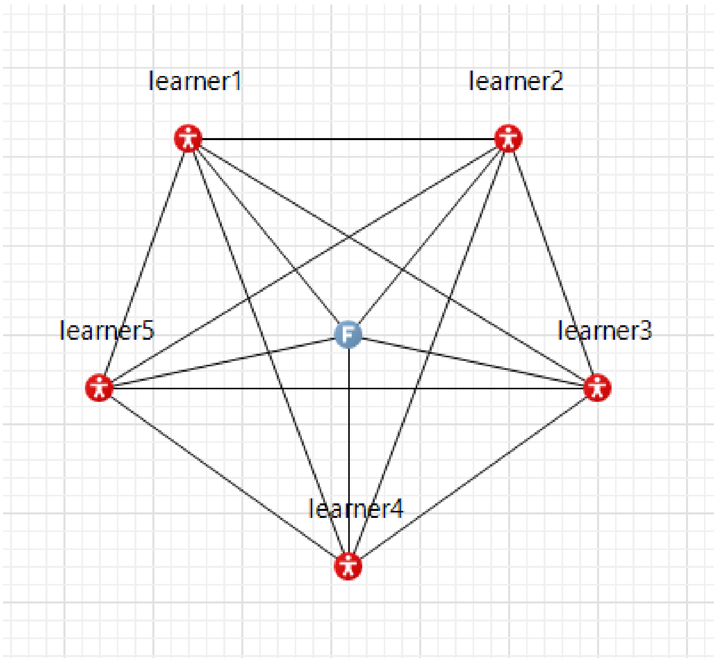
- Systems dynamics modeling
  - model systems at aggregate level using rates of changes and state variables
  - **strengths:** results easy to interpret; can be rapidly simulated
- Agent-based modeling
  - model individuals with their unique properties and interactions between individuals
  - **strengths:** easy to relate to results; useful for communication; can model systems in great detail
- The combination provides both structure and behavior

Acquiring data and modeling Learning Curves

- Statistical curve fitting
  - fit pre- and post-assessment data collected for various learning options to generate learning curves
- System Dynamics modeling
  - Optimize learning curve by performing sensitivity analysis
  - model individual student's learning and forgetting behavior
- Given data and an optimization metric, two approaches can be cross-verified and then used as an input to portfolio optimization

Generating and Analyzing Learning Curves

- Agent-based modeling
  - represent and track progress of learners/cohorts as they take courses using different learning options
  - Represent agents and their learning state



Statistical Curve Fitting

- Standard power function fit to learning curve data

$$y = ax^b + c$$

  - **y** is proficiency
  - **x** is customer's resource variable ($, time)
  - **a and b** control the shape of the curve
    - **a** controls height of curve
    - **0<b<1** (steep beginning, later flattening)
  - **c**: initial proficiency (when resource allocation is zero)

$$\mathbf{y_{online} = a_1 * t^{b_1}}$$

$$\mathbf{y_{inperson} = a_2 * t^{b_2}}$$

(with initial proficiency = 0)

Systems Dynamics Modeling: Assumptions

- Assumes learner takes a single course over n days
- Course taught using one or more learning options
- Learning options employed in preferred proportion for entire course
- Student learns course material for a specified time (e.g., 6 hrs) each day
- Student forgets a fraction of the material during non-learning period

Systems Dynamics Modeling: Learning and Forgetting

- Mathematical model:

$$LC_t = LC_0 + \sum_{t=1}^{n} (L_t - F_t)$$

  - LC_t is learner competency (or competencies) at day t of course
  - LC_0 is learner competency before course
  - L_t is learning (knowledge and skill) gained during day t
  - F_t is forgetting (knowledge lost) during day t
    - Note that $F_t = (LC_{t-1} * LF) * (1 - c)$
    - F_t is forgetting knowledge and skills during day t
    - LF is learner's forgetting rate per learning option

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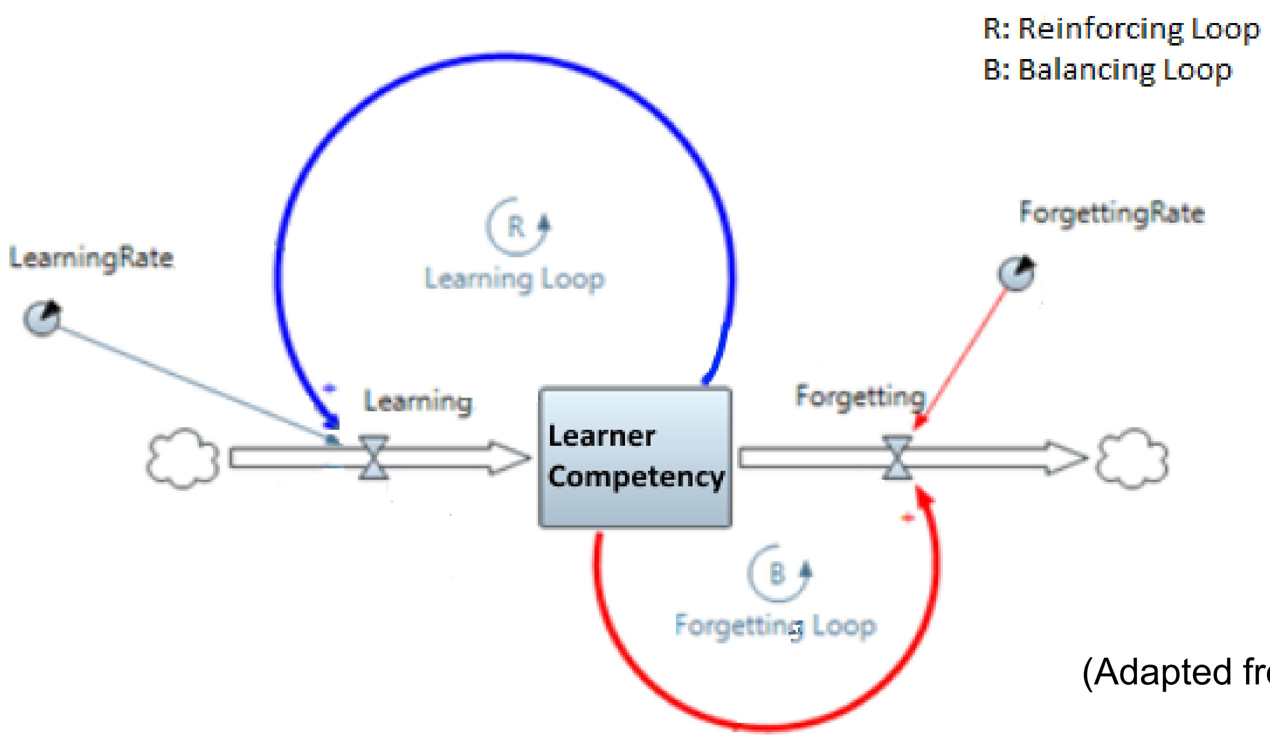
Systems Dynamics Modeling: Learning-Forgetting Behavior

- Assumes course taken over a specified period
- Learner spends a fraction of time per day on the course (e.g. 6 hours, or 25% of the day)
- Learner forgets some portion of material learned when not engaged in course
- Learner attributes
  - current competency level in course
  - pre-course competency level
  - learning rate (varies by learner and learning option)
  - forgetting rate
- Learner's competency re-evaluated daily

Systems Dynamic Model



(Adapted from Morrison, 2005)

Model Shows Learning and Forgetting Behavior

Optimizing Learning Curves

- Optimal allocation of funds and cohorts to learning options and courses
  - accelerate workforce development
  - accelerate time-to-proficiency for learner/job performer
- Can be formulated as a **portfolio optimization** problem
  - allocate a fixed resource (e.g. time, money) over several learning options to maximize overall proficiency/time to proficiency ratio
  - allocate some fraction (α_i) of available resource to each learning option, X_1 to X_n:

$$\max_{\alpha} \alpha_1 X_1 + \alpha_2 X_2 + \cdots + \alpha_n X_n \qquad s.t. \sum_{i=1}^{n} \alpha_i = 1$$

  - for example, if $\alpha_1 = 0.5$, then 50% of resources allocated to option 1

Portfolio Optimization

- A well-studied problem in management sciences
- Statistical methods can be extended to portfolio optimization
- Involves weighting each individual learning option (e.g., F2F, online) to achieve optimal allocation of fixed resources ($,time)
  - weights can be thought of as fraction of total $ or time allocated to each curve
- Assume proficiency is additive
  - Learning curves are distinct with no overlap (in proficiency gains)
- Proficiency function:

$$y = \sum_{i=1}^{n} a_i * t_i^{b_i} + c_i \ ,$$

$i = separate\ learning\ option/cohort\ combinatio$

Applying Portfolio Optimization

- Generally, the portfolio optimization problem is formulated to maximize some specific portfolio measure defined by the investor
  - e.g., portfolio return
- In our problem, initially we are less concerned with maximizing returns and more concerned with building a model in which investment options weights can be treated as “tuning” parameters
  - e.g., what happens if we increase/decrease w_1 ? How will the model change?
- After answering such questions, optimization can be performed for a variety of output variables

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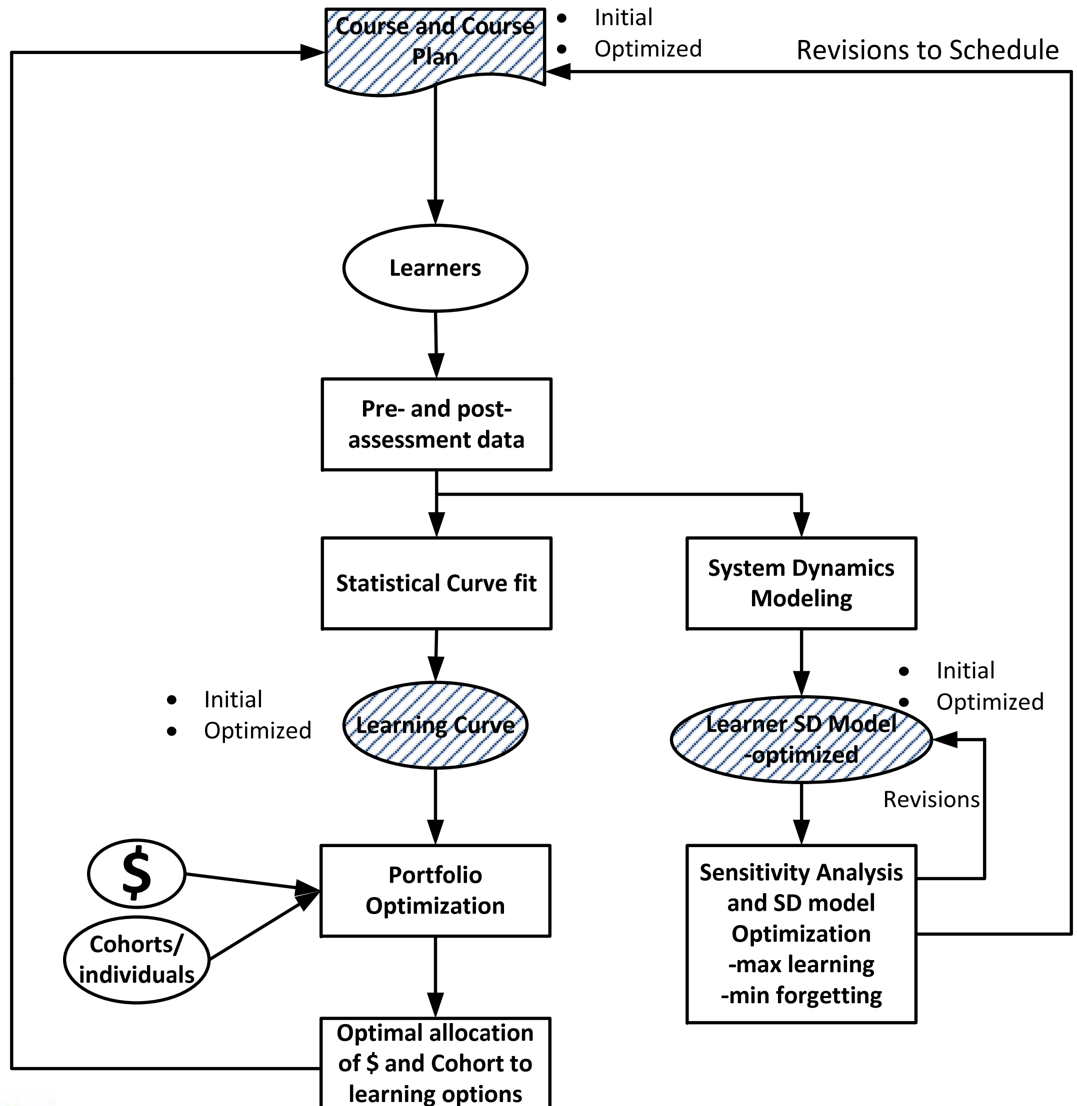
Methodology: Initial Experience



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Preliminary Data Collection

- Purpose: to formulate and structure the problem to collect insights
- Conducted by Boeing overseas
- Learners participated in two 12 hours long composite course
  - first course offered through WebEx in one location
  - second course delivered in person in a different location
- Learning format for first course
  - distributed model, prior reading and preparation, formal lectures online via the internet
- Learning format for second course
  - in-person, instructor-led, with prior preparation and formal lectures
- Same pre- and post-assessment for both formats
- Data collected from this study was used to calibrate learning curves and make an initial run of portfolio optimization algorithms
- Models fitted to data used to perform sensitivity analysis

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Preliminary Data Collection (cont'd)

- Each learning option has its own learning curve:

$$y_{online} = a_1 * t^{b_1}$$
$$y_{inperson} = a_2 * t^{b_2}$$

- Combined learning curve (total proficiency)

$$y_{total} = a_1 * t_{online}^{b_1} + a_2 * t_{inperson}^{b_2}$$

- Sample results*:
  - approximately 74% tested proficient overall

**Boeing study: small sample sizes and different testing procedures*

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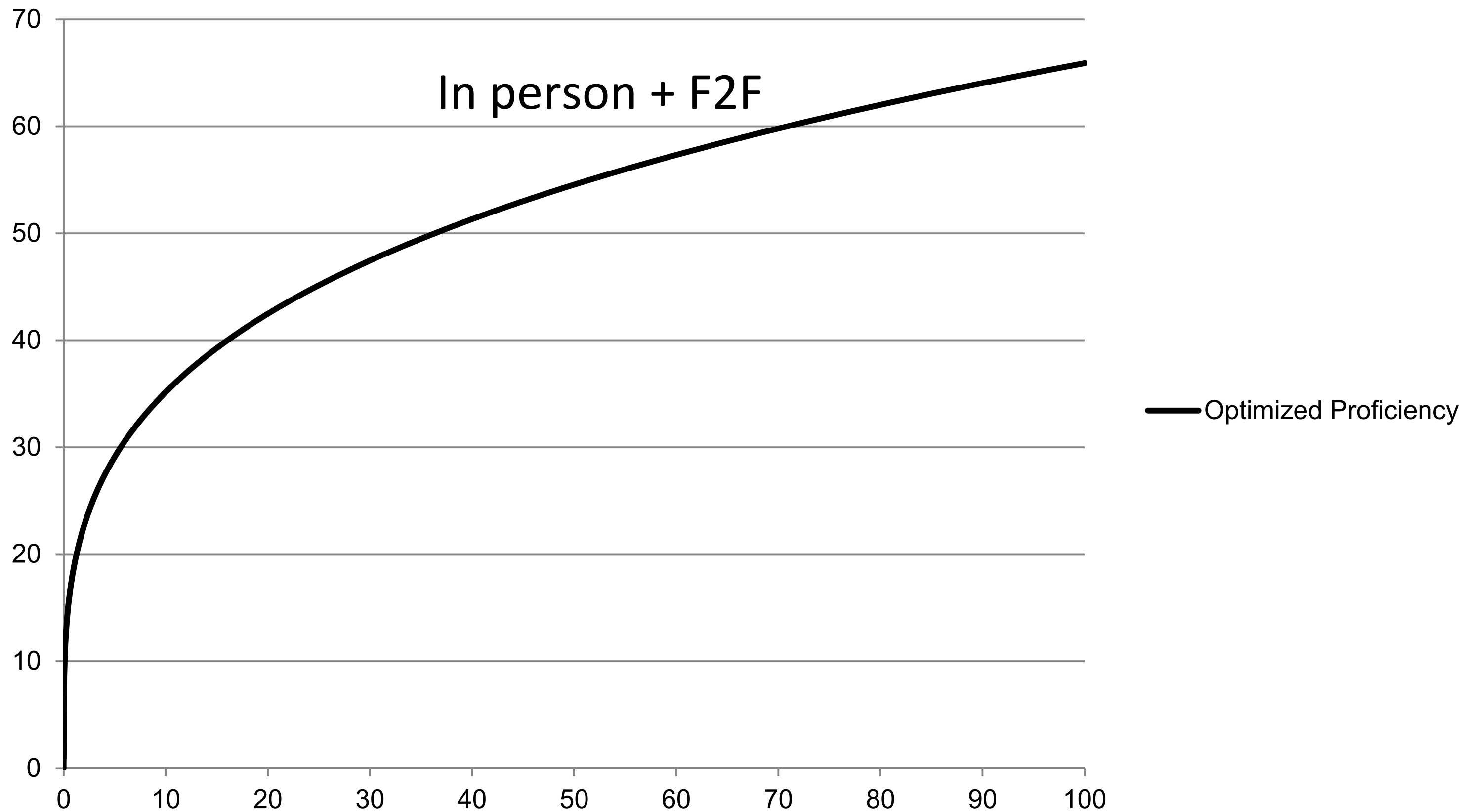
Preliminary Data Collection:
Combined learning curve



Optimized learning curve combining the two learning strategies:
a = 5.3375 , b = 0.2729, c = 0

Conclusion

- Learning curves graphically depict increase in learning with experience
- Learning curves have been used to **describe** learning that occurs in a production environment and in physical or virtual classrooms
- Learning curve concept is used in two ways
  - learning that occurs when same task is performed repeatedly over time
  - learning that occurs when a body of knowledge is accumulated over time
- We used learning curves as a **function to optimize** to accelerate learning
- Our approach combines statistical curve fitting, system dynamics modeling, portfolio optimization, and agent based modeling to create this capability
- Approach is being applied in a Boeing-sponsored research activity
  - Components of the approach were successfully applied in a Boeing pilot study conducted overseas

Way Ahead

- Expand data collection to include:
  - Pre-assessment
  - Mid-assessment
  - Post-assessment
- Incorporate clickers to collect data on each module
- Apply approach to two courses offered within Boeing
  - Process Design and Management
  - Systems Thinking and Complexity Management

Thank You