STB developmental Bridge: improve STEMM University CARED Outcomes (Grades 7-14)

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ABSTRACT

The author was an engineer for 20 years in both development and applications followed by 15 years as adult educator primarily at a Midwestern urban university with under-represented students. Beginning fall 2008 and for the next 7 years, he developed interventions for "under-prepared" STEMM (STEM and pre-Medical) students. This freshmen group entered with ACT math scores ranging from 14 to 21. By: Shaping cooperative peer learning, Teaching problem solving, and Building self-regulated learning; these under-prepared, often under-represented students overcame fundamental future achievement obstacles (i.e., calculus and core (major) coursework sequences). Projected improvement per regression discontinuity for a student at point of discontinuity (21.5 ACT math score) participating or denied treatment is + 30% (+ 0.6 GPA) in follow-up Calculus sequence and + 20% (+ 0.4 GPA) in majority of core coursework. STB *program* improvements for a 50% rate of participation: Completion: + 15%; Achievement (average): + 23%; Retention: + 21%; Enrollment: + 15%; and (Identity) Diversity: + 4.4%.

Keywords: cooperative peer learning, problem solving, self-regulated learning, student completion, student achievement, student retention, student enrollment, student diversity

PREAMBLE: A CALL TO EDUCATIONAL ACTION

"Growth comes through analogy; through seeing how things connect, rather than only seeing how they might be different." (Albert Einstein)

Teachers (educators) grades 5 through doctoral studies possess precisely the same 3 controls over those they lead as do CEOs of multi-national corporations and Brigadier Generals of the Armed Services. Consider a *balanced flow valve analogy*. Imagine three adjustable flow valves labeled as Social, Cognitive, and Metacognitive. If a proper balance is achieved; those being led (e.g., students, employees, or air/sea/land personnel) will be highly successful relative to *mission values* and the organization will thrive. If any of the three valves unduly restricts flow; the organization will flounder.

But what does proper balance mean in terms of interactions among Social, Cognitive, and Metacognitive factors? And once mission values are specified; what will be the *cost* in terms of additional teacher and student work efforts?

Now consider a *synchronized meshed gear analogy*. Gears are simple machines; a drive gear can cause a driven gear to generate more rotating force at a cost of drive to driven gear rotational speed. Two gears mesh as the teeth of one wheel lock into the teeth of another preventing the gears from slipping. The idea of a synchronized mesh among each of the Social, Cognitive, and Metacognitive factors will address the two questions above.

Extending a single plane two gear analogy to three gears (unless middle gear serves an idler function) simply does not work. In fact, no odd numbered planar gear combination does. However, there are several multi-plane three gear arrangements that do. The one most resembling the (STB) educational model is a triad of donut shaped linked gears; all turning together in an orchestrated synchronized dance (Youtube Numberphile Channel, 2016).

This paper will relate learning as it occurs in the classroom, on the manufacturing shop floor, and in military service. The goal is to answer an overarching question across these varied environments. What happens when Social, Cognitive, and Metacognitive factors are addressed well and what happens when they are not?

INTRODUCTION

(1) S: "As iron sharpens iron, so one person sharpens another." (Proverbs 27:17)
(2) T: "If you give a man a fish he is hungry again in an hour…but if you teach him how to fish…he will be richer all his life." (A. Isabella Ritchey, 1885; Taiwan missionary, 1961)
(3) B: "Many people dream of success. To me, success can only be achieved through repeated failure and introspection." (Soichiro Honda)

STB is an educational intervention model implemented in STEMM (Science Technology Engineering Math and (pre) Medical) disciplines in the environment of a Midwestern urban university with under-represented students. STB: (1) Shape (Cooperative Peer Learning), (2) Teach (Problem Solving), and (3) Build (Self-Regulated Learning) is intended to develop independent problem solving learners/leaders grades 7 through first 2 years postsecondary.

A Regression Discontinuity Design (RDD) was employed to make causal inferences on data from two STB intervention courses (ENTC 1500 & STEM 1513) for STEMM College freshmen. The treatment group presented as under-prepared (i.e., $14 \le$ ACT math score ≤ 21)

while the control group had ACT math scores of 22 and above. The Achievement effect on follow-up coursework was determined at the ***point of discontinuity*** (student with a 21.5 ACT math score) if student received or did not receive the relevant course treatment.

Regression Discontinuity is the appropriate causal alternative whenever a Randomized Control Trial (RCT) is impractical, not feasible, or if it is unethical to deny treatment to those control group members in need. The downside encountered in employing RDD rather than RCT involves the relative statistical power β associated with each design ($\beta_{RCT} \approx 2.5 \times \beta_{RDD}$).

Imagine an RCT study with sample sizes of treatment and control groups N = 40 students and $\alpha = 0.05$ (odds 1 in 20 observed outcome due to chance). If treatment magnitude (effect size) is just sufficient to reject the null hypothesis and conclude a real program effect exists then expectation for an RDD to reach same conviction at $\alpha = 0.05$ would require $N \approx 100$ students.

The immediate goal for each intervention was to improve achievement in subsequent relevant calculus sequence and core coursework (Engineering Technology for ENTC 1500 & Chemistry, Physics, and Biology for STEM 1513). The ultimate mission was to benefit overall ***program*** Completion, Achievement, Retention, Enrollment, and Diversity (CARED) outcomes.

Each of the three S, T, and B independent predictor variables is a ***mediator*** intended to address ***how*** the dependent CARED outcomes occur; the means, medium, or method for inducing outcomes. There are six independent ***moderator*** variables which explain ***when*** (under what boundary conditions) the CARED outcomes occur. Moderators can be perceived of as buffers or multipliers of mediating effects (Hayes, 2013; Jose, 2013).

For engineering technology students, the achievement improvements in follow-up courses at point of discontinuity were: (1) Calculus: + 0.57 GPA (2.383−1.809) or + 31.7% and (2) Core Coursework: + 0.42 GPA (2.510−2.086) or + 21.3%. For other STEMM students, the improvements were: (1) Calculus: + 0.64 GPA (2.585−1.950) or + 32.5%; (2) Physics: + 0.41 GPA (2.210−1.800) or + 22.8%; and (3) Biology: + 0.44 GPA (2.722−2.282) or + 19.3%. Average achievement bonus for the 5 measures (2 Calculus; 3 majors): + 25.3%.

For an STB intervention applied to 50% of incoming freshmen in greatest need (based on math preparation) ***program*** improvements attained were: Completion: + 15%; Achievement (average): + 23%; Retention: + 21%; Enrollment: + 15%; and (Identity) Diversity: + 4.4%.

This treatise attempts to explain how, when, and by what means CARED (Completion, Achievement, Retention, Enrollment, and Diversity) educational outcomes can be dramatically improved; at least in STEMM. Audience: (1) Practitioners of STEMM (STEM plus Medical) professions; (2) Educators grades 7 through first 2 years postsecondary; especially teachers of STEMM subjects; and (3) those interested in the interface between practice and education; specifically how lessons learned from the 80 year (1941 – Present) Quality Revolution offer guidance for development of robust ***sustainable*** educational processes. Detailed (historical) data for Achievement, Enrollment and Diversity were acquired for this study.

THE KEGAN DEVELOPMENTAL MODEL

"Now [2016] they [neuroscientists] talk about neural plasticity and acknowledge the phenomenal capacities of the brain to keep adapting throughout life." (Kegan & Lahey, 2016, p. 59).

The learning model adopted to understand underpinnings of STB was developed in the early 1980's by Dr. Robert Kegan. In an examination limited to adults, he modeled 3 separate qualitative plateaus in mental development: (1) Dependent Followers (Socialized mind), (2) Independent Problem Solving Leaders (Self-Authorizing mind), and (3) Interdependent Problem Finding Leaders (Self-Transforming mind) (Kegan & Lahey, 2016).

The intent of STB is to lift students from Dependent *socialized* Learners/Followers to *independent* Problem Solving Learners/Leaders. Prior to grade 7, in addition to teaching cognitive skills of reading, writing, and arithmetic; it is imperative to shape development of *socialized* learners/followers. That is, belief in virtues valuable to society at large; e.g., public service, civic/personal responsibility, optimism, imagination, hard work, and fair play. Post STB, education should transition into a pure form of inquiry based teaching & learning. That is, promote the critical thinking and creativity necessary to integrate *social* and *independent* precursor aspects to develop *interdependent* learners/leaders (problem finding leaders).

Per Kegan's model, the initial phase change (*socialization* to *independence*) is not the end goal; the follow-up phase change to *interdependence* is. See Figure 1 end of article.

AFFINITY AMONG SOCIALIZATION, INDEPENDENCE & INTERDEPENDENCE

"Interdependence [the 3rd aspect] is and ought to be as much the ideal of man as self-sufficiency [the 2nd aspect]…. Man is a social being [the 1st aspect]…. Dependence on society teaches him the lesson of humanity." (Fisher, 2002, pp. 168, 169) Gandhi, *Young India*, March 29, 1929.

The Langdellian "Socratic" Method instituted at Harvard University's Law School in 1872 reflected the conclusion that rote memorization of judicial rules was insufficient for students to attain an understanding of legal principles. Instead, students needed to discern how such rules evolved out of specific factual conditions. Deductive *independent* reasoning was employed to provide the means to indelibly etch essential legal principles on each student's mind. An early student of this radical style of learning and law practice, Louis Brandeis (1856-1941) adhered to grounding the law in "all the facts that surround", detailed preparation, and multi-factor deductive analysis. Moreover, as practitioner, reformer and jurist; experience informed Brandeis that the *interdependence* of forming organizations, raising/creating public opinion, and fashioning a solution fair to all were necessary to move from a well-reasoned concept to an implemented reality where the public owns the reform (Urofsky, 2009).

Across the globe, another reformer trained in the British tradition of the law; Mahatma Gandhi (1869-1948) would marry political and spiritually based theories of freedom giving rise to dramatically successful civil rights movements in India, the U.S. and South Africa. He modeled an inspirational and aspirational message for all humanity; develop, then integrate *social*, *independent* (i.e., self-sufficiency), and *interdependent* aspects of virtuous character.

Students generally enter college as dependent *socialized* learners. University educators typically are satisfied to facilitate growth from *socialized* learners/followers to *independent* learners (problem solvers) who take responsibility for their own learning. Additionally, students should be encouraged to recognize and respect interrelationships of disparate ideas in preparation for a projected future environment with diverse peer co-workers.

Graduates will then enter their chosen field with an appropriate skill set of *how* to solve problems. Field experience will fill in: (1) *Who* can help provide direction when an impasse occurs; (2) *What* information is essential and *what* is superfluous; (3, 4 & 5) *When* & *Where* can the skill set be applied; and *Why* not over here? By such exposure graduates should be afforded opportunities to develop into *interdependent* leaders.

IMPACT OF EACH STB MEDIATOR IN ISOLATION ON ACHIEVEMENT

(1) S: "Nothing new that is really interesting comes without collaboration." (James D. Watson)
(2) T: "A problem well-put is half solved." (John Dewey); "The formulation of the problem is often more essential than its solution." (Albert Einstein)
(3) B: "Actively self-reflecting on the approaches that you are taking … can make the difference between people who achieve and people who have the potential to achieve, but don't." (Patricia Chen, Art collection historian)

John Hattie's *Visible Learning* (2009) is a key reference for understanding by what means STB (optimal class size 12 to 30) produces the dramatic achievement improvements chronicled earlier. Hattie's work synthesized 800 meta-analyses based on 50,000 studies and millions of students related to achievement. He introduced the concept of a *hinge point* to denote effect sizes, $d \geq 0.40$ as a guideline necessary to observe *visible* student change. "[T]eachers [left to their own devices] typically can attain between $d = 0.20$ to $d = 0.40$ [achievement] growth per year" (Hattie, 2009, p. 17).

The first STB *mediator*, Social: Shape cooperative peer learning per Hattie's synthesis has effect size, $0.41 \leq d_{ACHV} \leq 0.59$. The second STB *mediator*, Cognitive: Teach problem solving carries effect size, $0.61 \leq d_{ACHV} \leq 0.71$. The third STB *mediator*, Metacognitive: Build self-regulated learning carries an effect size, $d_{ACHV} = 0.69$.

Shape: Cooperative and competitive *peer learning* are more effective than individualistic learning. Regardless of learning environment, the majority of feedback students receive is from other students. Both peer learning forms can and should be employed but in a head to head comparison; cooperative learning is more effective, $d_{ACHV} = 0.54$. Unless intentional structure is supplied; much if not most feedback from peers will be false and/or misleading. If, as in the two interventions, structure is provided then the power of peer learning can be unleashed.

Teach: Inquiry Based Teaching overall $d_{ACHV} = 0.31$; higher in biology ($d_{ACHV} = 0.30$) and physics ($d_{ACHV} = 0.27$) than chemistry ($d_{ACHV} = 0.10$). Compare with $0.61 \leq d_{ACHV} \leq 0.71$ for Problem Solving Teaching. It is the *critical thinking skills* impact, $d_{CRIT\ THINK} = 1.02$ that attests to the potential of Inquiry to lift learners from *independent to interdependent* and commends its use in upper level undergraduate STEMM coursework.

Build: John Flavell, American disciple of Jean Piaget, coined the term metacognition in 1976. He defined metacognition as the ability to transform mental processes through planning, goal setting, and reflection to become self-critical, self-monitoring, self-assessing, and self-regulating. *Metacognitive strategies promote strategic practices, tools, and methodologies*. A methodology seeks to understand which method, set of methods or best practices can be applied. Self-Regulated Learning involves self-selection and self-monitoring of appropriate tools and *adoption of method(s) well-suited to types of problems to be solved*.

TRANSITIONS TO AND FROM STB

"Life is not primarily a quest for pleasure as Freud believed, or a quest for power, as Alfred Adler taught, but a quest for meaning." (Viktor Frankl)

Metacognitive studies show that up until the age of 11 (grade 5); the capacity of the mind to reflect on its working operation is beyond the child's developmental level. Moreover, prior to middle school age, value of homework as an effective practice (Mod 6 Figure 4 end of article) is low; i.e., age *moderates* homework effect on achievement. Since grade 7 is the typical entry point to spark a serious scientific inquiry; grade 7 provides a natural STB starting point.

The second handoff; from STB to Inquiry Based Teaching should be seamless since cooperative peer learning "lab experiences" take students from Structured Inquiry into Controlled Inquiry. Next logical steps are Guided and Free Inquiry. By designing upper level coursework with the end in mind; i.e., Free Inquiry; student group project proposals, reports, and presentations can replace traditional summative final exams (Mackenzie, 2016).

Capstone requirements are a culminating set of experiences set in the senior year of college when students synthesize, integrate and/or apply previously acquired knowledge so as to demonstrate mastery. There are three popular *formats*: (1) Students from 2 or more disciplines (cognitive diversity) are paired to complete an interdisciplinary project; (2) Students from a single discipline pull knowledge gained from multiple previous courses and/or off site experiences; and (3) Students document learning in relation to industry standards (e.g., as part of in-the-field apprenticeships or co-ops). Each of the three formats would be well served by prior student exposure to Inquiry Based Teaching & Learning.

In summary, STB by development of *independent* thought can act as bridge between phase 1 *socialized* mind (K-6) and phase 3 *interdependent* mind [Inquiry Based Learning (upper-class under-graduate level and beyond)]. Hence, the sweet spot for STB is grades 7-14.

MORE SIMPLE ANALOGIES FOR STB TEACHING & LEARNING

"When you add a goal to the enjoyment of what you do … tension is now added to enjoyment, and … turns into enthusiasm. At the height of creative activity … you will feel like an arrow … moving toward the target … enjoying the journey" (Tolle, 2005, p. 301).

The Social: <u>S</u>hape cooperative peer learning, Cognitive: <u>T</u>each problem solving and Metacognitive: <u>B</u>uild self-regulated learning mediators are interdependent. The *synchronized meshed gear analogy* applies. For example, Cognitive: <u>T</u>each problem solving in isolation has effect size $d_{\text{ACHV}} = 0.61$. The upper level effect size, $d_{\text{ACHV}} = 0.71$ is attained *only* when meshed with a suitable method integral to the Metacognitive gear.

Many to most STEMM college courses are heavy on the Cognitive aspect while Social and Metacognitive aspects are minimal and in the case of Social often discouraged. How much additional effort is required by educators and students to fully integrate the Social and Meta-cognitive along with the Cognitive? It turns out that when all 3 gears truly are dynamically in play; the extra effort predicted (and experienced) is around 25%.

If as a pure cognitive educator, you are putting in 40 hours per week performing your inside and outside the classroom tasks; expect your workload to ratchet up to 50 hours per week. Of the two intervention classes the author will be discussing in depth; the first, ENTC 1500 for engineering technology students met 6 academic hours per week; the second, STEM 1513 met only 3 academic hours per week. The extra effort placed on the ENTC 1500 students was largely absorbed within scheduled class time; STEM 1513 students did not have that advantage. Based on lessons learned (e.g. spaced vs. massed lab write-ups); a double block (i.e., 2 hour in class time, twice per week) would be a practical time schedule for such intervention endeavors.

The teacher's theatrical equivalent function can't simply fulfill the role of *sage on the stage*; it must expand to *guide on the side* (mentor) and *set designer* to bring into reality the experiential group and individual practice aspects necessary to Shape cooperative peer learning and Build self-regulated learning. So, is this 25% higher effort in time and teacher development of new capabilities as guide and set designer warranted? Based on quantitative evidence of improvement in student Completion, Achievement, Retention, Enrollment, and Diversity; the answer is yes. Based on qualitative effects (see quote above); the answer is a resounding yes.

Turn now to Figure 3, the STB causal model. Shaping Cooperative Peer Learning by way of group experiences aligns with Diversity while Building self-regulated learning and the associated discipline of individual practice line up with Resilience. For the other four outcomes, Achievement stands out as lead indicator for lag outcomes of Retention, Enrollment and Completion. The STB combination effectively promotes flexible movement among surface, deep, and transfer knowledge.

Achievement is modeled by three equal linearly weighted inputs (i.e., S, T, and B). Retention: ½ Achievement & ½ Resilience; Enrollment: ½ Achievement & ½ Retention; and Completion: ⅓ Achievement, ⅓ Enrollment & ⅓ Retention. Diversity promotion (discussed later) is a more complex nonlinear consequence (function) of Social: Shaping cooperative peer learning. Figure 4 contributes the extra layer of *moderators* (boundary conditions) that explain the *when* behind the *how* STB mediators.

A DEEPER ANALOGY FOR STB: THE QUALITY REVOLUTION (1941 – 1980)

Characterizations on the role played by frontline workers:
A dichotomy: Separate planning from execution vs. Encourage bottom up planning.
Taylor: "We pay you to perform work not to plan or think."
Deming: "Nobody understands the job as well as the person who does it day in and out."

The "father of Quality Control", Walter (W.A.) Shewhart (1891-1967) developed statistical theory, tools and visuals for understanding and monitoring process variation (e.g., control charts) while at Western Electric and Bell Labs between the 1920s and early 1940s. During World War II, he helped launch the first quality revolution; part of the U.S. military manufacturing productivity effort. After the war, this effort was discontinued as U.S. manufacturing reverted back to the Scientific Management (efficiency) model developed by Frederick Taylor (1856-1915).

Two individuals mentored by Shewhart in statistical process control, William Edwards (W.E.) Deming (1900-1996) and Joseph (J.M.) Juran (1904-2008) were instrumental in launching the 2nd wave of the quality revolution; in 1950s Japan. Shewhart and Deming held undergrad degrees in engineering & doctorates in physics; Juran's background was in math, engineering and law. All developed statistical expertise by self-training and collaboration.

Deming in collaboration with Shewhart, Juran, Ishikawa, and Crosby developed five core principles: (1) empowerment of front line workers, (2) promotion of teamwork, (3) creation of a *secure* (literally without fear) [of failure] environment, (4) evidence based continuous improvement (always more to learn), and (5) deliberative practice. Ishikawa (1962) distilled the first 3 principles which he felt promoted social *joy in the workplace* into Quality Control (QC) Circles; groups of 3 to 12 front line workers with similar production interests who met regularly to discuss, address and problem solve manufacturing issues.

In the 1950s, Deming developed a method appropriate to problem solving by QC Circles to mesh with the cognitive *mediator* of continuous improvement (Kaizen). This Learning Cycle is PDCA: Plan a change or test, Do the change or test, Check or study the results (What went wrong? What went right?), and Act (Adopt or Abandon the change?). Since this is a cycle and there is always more to learn; the wheel keeps on turning. See Figure 2 end of article.

The concept of continuous improvement reflects the persistent human desire to do better (to grow). Resiliency to accept failures and keep the wheel turning can be advanced by seeking help from mentors and/or peers (e.g., members of the QC Circle). When setbacks occur; "resilience, the ability to sustain ambition in the face of frustration [transcending public and private adversity is] at the heart of potential leadership growth" (Goodwin, 2018, p. 97).

The quality (organizational performance) outcome can be perceived as *mediated* by 3 predictor variable components: *Social* (QC Circles), *Cognitive* (Continuous Improvement), and *Metacognitive* (Deliberative Practice). So, a one to one mediator correspondence (Social, Cognitive, and Metacognitive) exists between 2nd wave Quality Revolution and STB. Is there an STB problem solving learning method analogous to shop floor QC Circle PDCA?

A PROBLEM SOLVING METHOD FOR STB & AN ALTERNATIVE PERSPECTIVE

"Growth occurs when individuals confront problems, struggle to master them, and through that struggle develop new aspects of their skills, capacities, [and] views about life." (Carl Rogers)

The six step Engineering Problem Solving Method (circa 1945) is as follows:

(1) Given: [Known Facts]
(2) Find: [Unknown Facts]
(3) Sketch or Table?: [Visualization]
(4) Equation(s): [Relationships]
(5) Plug THEN Chug: [Calculations WITH Units]
(6) Units & Reality Check: [Estimation & Interpretation]

The *six step method* has been routinely taught to students in engineering and engineering technology in the U.S. going back at least to the end of WW II. Both PDCA and the six step method stress *synthesis*; *divergent* thought which operates like a *spray or diffuser*. Begin by framing a problem description; i.e., Plan or Given/Find. Seek to find *many* possible *prototype solutions* (Rutherford, 2019). These are then *aggregation methods* tailor-made for new and unusual situations.

Manufacturing problems encountered by application engineers and frontline shop floor workers typically are constrained by time and limited immediate options. Under the best of conditions (production flow unimpeded); the troubleshooting goal is to find a better way; not an optimum solution. Experiential exercises of balancing lines, revising operational flow, modifying tools and general tinkering are hallmarks guided but not constrained by either six step or PDCA methods. The upcoming discussion on Lean Manufacturing will show a similar philosophy. Let's then group six step, PDCA, and Lean as ***Experiential Divergent Methods***.

The author is aware of only one discipline that has created an alternative to the six step method: Chemical Engineering. The 1979 McMaster 5 point strategy was based on dissatisfaction arising in the 1960s from a firmly held belief that Chemical Engineering students were not learning to solve the types of problems they would encounter in the field:

(1) Define [Identify objective, constraints, and standard(s) of *measure*.]
(2) Explore [Id connections/relevance/outcomes. Guess answer. Redefine *measures*.]
(3) Plan [Select rules of thumb. Develop *algorithm*. Assemble resources.]

(4) Act [Follow the Plan. Evaluate alternatives. Pick best alternative.]
(5) Reflect [Errors? Reasonable result? True to procedure? Provide results.]

The McMaster 5 point strategy embodies ***analysis***; ***convergent*** thought operating like a ***funnel.*** Pare a large number of distinct options down to a smaller and smaller number ultimately arriving at a ***single optimal solution*** (Rutherford, 2019). This is a ***reductive method***.

The McMaster 5 point strategy is a rigid heuristic aspiring to an algorithm. The goal is to examine a plethora of options, diagnostically sort out best alternatives, and then by careful, deliberate measurements on validated instruments develop a best (breakthrough) solution. This makes sense in context of relative isolation of lab work or purely financial number crunching vs. collaborative shop flow experiences. The upcoming discussion on Six Sigma will show compatibility between these two. Let's then group the McMaster 5 point strategy and Six Sigma as *Analytical Convergent Methods*.

VISUAL TOOLS FOR 2ND WAVE OF THE QUALITY REVOLUTION (1950 – 1980)

"Visual management charts must allow for communication and sharing … [they do] not work if only one person uses that information." (Ichiro Suzuki, chief engineer of first Lexus (Toyota))

"Seven graphical techniques" were developed to aid as troubleshooting tools for 2nd wave burgeoning Quality Circles: (1) Tally (check) sheets; (2) Histogram (frequency) charts; (3) Juran's Pareto (sorted frequency) charts; (4) Deming/Shewhart control (average & range) charts; (5) Ishikawa's fishbone (cause & effect) diagrams; (6) Scatter diagrams; and (7) Flow charts & Run (time series) charts (Juran, 1992).

In the field of economics, it was established in the early 1900's that a relatively small group of individuals controlled a large percentage of both national wealth and income. Juran (1904-2008) recognized that quality defects follow the same distribution pattern as income inequality. If a long list of causes for defects is arranged in order of frequency (graphical technique (3) above); the top 20% of causes account for the bulk (roughly 80%) of defects.

Dorian Shainin (1914-2000), an MIT trained aeronautical engineer, a friend mentored by Juran also recognized the significance of this distribution in the field of product reliability. It was Juran who named the 80/20 rule of thumb after Vilfredo Pareto (1848-1923) as the Pareto Principle. Pareto who studied the Italian economy was arguably the first evidence based economist. As Shainin pointed out to Juran this might be a misattribution. In 1905, American economist Max Lorentz (1876-1959) developed the model for a set of characteristic curves revealing the nature of income inequality. One of these characteristic curves (McKey, 2019) was used to generate participation rate weighting factors to convert each of the ***raw*** CARED outcomes into ***program*** (Engineering Technology or other STEMM) outcomes.

To illustrate the potency of the Pareto Principle: Vacuum sweepers for home use are run on average 70 minutes per week. Over 10 years, this amounts to roughly 600 hours of operation matching the brush life of the series universal motor typically employed. Frequency of failures occurs in a washtub style pattern [numerous early failures, a long useful life, and end of life (brush wear out)]. The same pattern holds for life characteristics of tires, flat screen TVs, etc.

A study was undertaken determining 20 failure causes (modes) responsible for early sweeper motor failures; those not due to brush wear out. These were grouped by frequency in a Pareto chart. The top 20% (0.20 x 20 = 4) failure causes were focused on and driven down (by product design and/or manufacturing process improvement) ***below the rate of the 5th cause***. The result was an improvement in early life failures of roughly 80%. The top 20% of causes were responsible for a full 80% of the problem (failures)!

Are there similar critical visual tool(s) to both understand and implement STB? That is equivalents to the Lorentz curve for understanding and the seven graphical techniques for arriving at multiple solutions to problems addressed on the manufacturing shop floor.

CRITICAL VISUAL TOOLS TO UNDERSTAND & IMPLEMENT STB

"The greatest value of a picture is when it forces us to notice what we never expected to see." (John Tukey)

The sections of a formal lab report (following the Cover Sheet and Table of Contents)

(1) Description of Apparatus
(2) Test Procedure
   a. As provided by instructor (for these interventions)
   b. Student Bulleted Procedure (useful learning tool)
(3) Results
   a. Tables (Tabular Data)
   b. Charts (Graphs or Sketches)
(4) Analysis of Results
(5) Sample Calculations
(6) Original Data Sheet(s)

The earliest discovered data table dates back to 150 AD. They are textual data representations using visual attributes of alignment, white space, and sometimes horizontal and/or vertical rule lines. Tables along with diagrams and graphs are classified as charts. Tables served as mankind's initial nudge shifting data form from textual to graphical (Few, 2009).

Sketches and/or tables are strongly encouraged in Step (3) of the 6-step method discussed earlier. For labs; sketches (or photos) are common in Section (1): Description of Apparatus while tables, sketches, and graphs [e.g.; part sketches, scatter diagrams (usually with curve fits), histograms, and bar graphs] make up the entirety of Section (3): Results.

A review of Jo Boaler's 2016 *Mathematical Mindsets* suggested inflection points along the K-16 educational path. Initially, the relationship $y = x^3$ came to mind. The problem is the inherent flat that occurs. The two inflection points typical in Midwestern STEM public education correspond to 7th grade science and high school intermediate algebra (Algebra 2). While slope change is less dramatic during assimilation of the essence of these two milestone subjects; flat they are not. A rotation of 90° followed by a mirror image of a rough sketch of the K-16 educational path transformed the picture into a logistic ∫ curve. John Tukey was right!

Here is the first appearance of the ∫ curve applicable to understanding the full arc of the K-16 journey. The ∫ curve will pop up again when examining the role of deliberative practice (homework). Refer to Figure 3 which indicates that the foundational mediating Metacognitive: Build self-regulated learning block feeds directly into student Resiliency.

Moving from cumulative percentages to absolute numbers over time; the ∫ curve morphs into a normal distribution. The path taken when a student moves from novice to below basic to above basic to proficient to expert (appropriate to a normal distribution) is the ∫ curve. Factoring in the rule of thumb that 10,000 hours of practice is necessary to move from novice to expert for even the most "gifted" individual implies 6 years practicing 45+ hours per day, 5 days per week. In other words, the equivalent of a full time job for 6 full years!

Notice that Section (4) of the lab report Analysis of Results (4th in submission order but last section written) utilizes an Analytical Convergent Method. The bulk of the report employs the Experiential Divergent Method. This will provide a key insight when considering the impact of STEM 1513 on chemistry achievement.

EFFECT OF SOCIAL, COGNITIVE & METACOGNITIVE ON ACHIEVEMENT

"[W]hen students learn how to gain an overall picture of what is to be learnt, have an understanding of the success criteria for the lessons to come and are somewhat clear at the outset about what it means to master the lessons, then their subsequent learning is maximized" (Hattie & Donoghue, 2016, p. 6).

John Hattie collaborated with Gregory Donoghue on the 2016 article quoted above which identified over 300 personal learning strategies related to achievement based on 200+ meta-analyses (sample size 13 to 20 million students). In 1997, Boekaerts made a strong argument for the critical nature of metacognitive learning strategies. Her position was that Motivational, Cognitive, and Metacognitive strategies would likely form the most potent blended combination for students to enhance their own learning.

The Hattie & Donohue article provides strong evidence confirming central roles of both the Cognitive and Metacognitive mediators as powerful agents for Achievement. On the other hand, Motivation which carries an effect size, $d_{ACHV} = 0.34$; falls short of two interrelated student needs: (1) understand what relevant student success looks like and (2) be able to acquire and consolidate appropriate levels of Surface, Deep, and Transfer Learning.

(Student knowledge of) Success criteria based on nearly 3,400 studies involving over 400,000 students carries effect size, $d_{ACHV} = 0.55$. Subsumed within Success criteria (top 6 of 9) are Planning & prediction, Intent to implement goals, Concept mapping (*when* developed with students), Setting standards for self-judgment, and Difficulty of goals; $0.57 \leq d_{ACHV} \leq 1.13$.

The left side *moderators* (Figure 4 end of article) explain the *when* behind the *how* of Shaping cooperative peer learning and subscribe to (Student knowledge of) Success criteria. Moderators: Mod 1 [Rapid (2-way) Student/Teacher Feedback], Mod 2 [Student/Teacher Relationship], Mod 3 [Formative Evaluations], and Mod 4 [High Expectations].

As to Acquisition & Consolidation of Learning, $0.53 \leq d_{ACHV} \leq 1.09$ based on 9,000 studies (over 10 million students). The top 5 approaches for *consolidating* surface learning: (1) Deliberate practice, (2) Effort, (3) Rehearsal/memorization, (4) Giving/receiving feedback, and (5) Spaced versus massed practice; $0.60 \leq d_{ACHV} \leq 0.77$ (Hattie & Donoghue, 2016).

In order to acquire deep learning, 3 of 5 approaches were categorized as falling within the metacognitive realm (Strategy monitoring $d_{ACHV} = 0.71$, Metacognitive strategies $d_{ACHV} = 0.61$, and Self-Regulation $d_{ACHV} = 0.52$). Five of the top 11 approaches to consolidate deep learning ($0.64 \leq d_{ACHV} \leq 0.83$): Seeking help from peers [fits with Social: Shape cooperative peer learning], Class discussion, Evaluation & reflection [fits with Mod 3 Formative Evaluation], Self consequences [fits with cooperative peer learning lab obligations], and *Problem Solving Teaching* [emphasis added to cognitive approach implemented in both STB interventions].

Now let's move on to examine the role and nature of the *3 individual gears* which will subsequently be *synchronously meshed* into a *dynamically balanced assembly*.

IMPLEMENT SOCIAL: SHAPE COOPERATIVE PEER LEARNING

"Play is the answer to how anything new comes about" (Jean Piaget).

To repeat, the first STB *mediator*, Social: Shape cooperative peer learning per Hattie's synthesis has an effect size, $0.41 \leq d_{ACHV} \leq 0.59$. There is a dosing (threshold) effect of 5 cooperative small group "lab experiences" necessary to ground this mediator. Author prefers a ratio of class size to lab group size in the range of 10 to 12. Example: For class size 24; 12 groups of size 2; for class size 30; 10 groups of size 3.

Lab partners don't automatically share identical lab grades; they are required to document "who did what?" on each report. There are consequences for missing lab time or late submittals. Lab designs should promote analysis or creativity; ideally both. Teacher demonstrations are not substitutes for direct student group labs in the peer learning and inquiry they advance.

IMPLEMENT COGNITIVE: TEACH PROBLEM SOLVING

"The measure of success is not whether you have a tough problem to deal with, but whether it is the same problem you had last year" (John Foster Dulles).

Precepts for: Teaching problem solving in an experiential STB environment:

(1) When developing experiential experiences to illustrate overarching concepts (e.g., Conservation of Energy) strive to create a crystal clear visual pattern so compelling that it burns itself (like a photograph) into students' memories.
(2) Expert field practitioners approach problem solving in 3 distinct modalities: (1) Repetitive *auto-pilot*, (2) Novel real time *problem-solver*, and (3) Contemplative *reflective-detective* frequently asking: *Why* did this particular solution *fail*?
(3) Understanding problem solving; e.g., how to attack novel problems is a great gift educators can impart.
(4) When experts vs. novices approach novel problems; they employ *sense making before solution* drawing on *metacognitive practices, tools & methods*.
(5) Landmark complex problem solutions break across biases and organizational silos; e.g., via cooperative peer-learning bridging diverse perspectives.

IMPLEMENT METACOGNITIVE: BUILD SELF-REGULATED LEARNING

"Learning is about … one's ability to exert the effort, self-control, and critical self-assessment necessary to achieve the best possible results … in pursuit of REAL achievement" (Linda B. Nilson)

Deliberative practice was implemented in STB relative to *moderator* Mod 6, Homework. Specifically, for both ENTC 1500 and STEM 1513, author consistently required 12 homework assignments (HW Set #1) during the first half semester (score best 10 of 12). Despite *HW Set #1* counting only 5% of *final course grade*; there is a strong correlation between the two measures.

Once this correlation was uncovered, it was shared with students on the first day of class; emphasizing the rarity of students falling below a C overall grade (3.3%) when their first half homework score was 67% or above. More striking, by a small additional 8% improvement (67% to 75%); most students moved from a C to a B course grade. This suggests final course grade vs. practice in the form of HW Set #1 may be tracing out a logistic ʃ curve. Effort flows naturally from the *moderators*: Mod 4, High Expectations and Mod 1, Rapid (2-way) feedback, Figure 4. Early in the development of the STB approach, a conscious effort was made to move from massed to spaced practice; e.g., longer time to work on lab report writing prior to submittal.

The Build self-regulated learning *mediator* promotes student knowledge: (1) *how* to approach and maximize scores on technical exams, (2) significance of deliberative practices [(a) homework performed to *6 step method* and (b) the value of self-testing], (3) importance of showing up (i.e., attendance) [(a) for lab exercises (group benefit) and (b) test evaluations (individual benefit)], and (4) concept and impact of self-regulation.

ASSEMBLING STB: BALANCING FLOWS AND MESHING INTERCONNECTIONS

"To become wise you've got to have models in your head. And you've got to array your experience--both vicarious and direct--on this latticework of models." (Charlie Munger)

While the three STB mediators explain how CARED outcomes occur; it is the six moderators (Figure 4) that buffer or multiply their impact. Moderator 2 (The Student Teacher Relationship) has a direct impact on the lab effect promoting Social: Shaping Cooperative Peer Learning. Moderator 6 (Practice) plays the same role developing Metacognitive: Building Self-Regulated Learning. Moderator 1 (Rapid Feedback) directly impacts both the Social and Metacognitive mediators.

In application, these three moderating factors explain the most common failings that undermine maximizing outcomes:

(1) Lab Effect: (Moderator 2)
(2) Practice Effect: (Moderator 6)
(3) Rapid 2 Way Feedback Effect(s): (Moderator 1)

Violation of (1) [Lab Effect] occurs if instructor is not diligently promoting and prioritizing lab experiences grounded in a solid student/teacher relationship. The author ensured fulfillment of a full complement of 5 labs for each intervention. Per left side of causal model (Figure 3) negative impacts will be primarily on Diversity, and secondarily on Achievement.

Breach of (2) [Practice Effect] equates to failure to activate student efforts on a full array of first half semester homework. Grading what are primarily word problems, should heavily weigh applying the 6-step method (discussed 5 pages previous); not focusing on "right" or "wrong" answers. Grading of formative exams (Moderator 6) should follow the same tact. Per right side of causal model (Figure 3) negative impacts will be primarily on Resiliency, and secondarily on both Retention and Achievement.

Failure to provide (3) [Rapid 2 Way Feedback] can have twin detrimental effects: (a) if it depresses the Lab Effect; (b) if it impairs the Practice Effect. This is why the *Rapid Feedback* block is split in Figure 4; it serves a critical *dual moderation* (constraint) role. If (a) occurs then the muting of outcome effects will match with (1) [Lab Effect]; if (b) then (2) [Practice Effect].

Ultimately, it is both *balanced flow* and *synchronized mesh* among Social, Cognitive & Metacognitive (S, T, and B) that boosts students' capability to quickly, efficiently, and seemingly effortlessly shift among Surface, Deep and Transfer knowledge.

IMPLICATIONS OF 3RD WAVE OF QUALITY REVOLUTION (1981 – 1995)

"We must stop setting our sights by the light of each passing ship; instead we must set our course by the stars." (Gen. George C. Marshall)

The 3rd wave of the quality revolution owes its genesis to a 1980 NBC television documentary, ***If Japan can why can't we***? The reconstituted program to address the demise of the 1st wave (post WW II) in the U.S. and lessons learned in the 2nd wave in Japan was now termed Total Quality Management (TQM). The five gurus (Crosby, Deming, Ishikawa, Juran, and Shewhart) of the 1941−1980 Quality Revolution were discussed 6 pages previously. Juran in particular, noted that absent full upper management buy in and participation; any long term quality revolution was doomed to fade as evidenced by the rapid decline of the 1st wave.

The Air Force Tactical Air Command (TAC) was an early adopter of TQM. In 1981, Gen. Bill Creech convinced the USAF to convert this branch into a decentralized TQM model. In 1991, Gen. Homer attributed air success in the First Gulf War to a decade long TQM *culture*.

By 1995, TQM became dysfunctional within the Air Force due to a post-Cold War/post-Gulf War teardown. Termed a tsunami event in a 2009 retrospective study; seven factors were cited: (1) budget cuts; (2) manpower reductions; (3) compliance directives; (4) reorganizations; (5) personnel turnover; (6) mission growth; and (7) shift from quality to an emphasis on forms submissions and test scores. Not only did TQM die on the vine in the USAF but it largely lost its constancy of purpose throughout U.S. industry by 1997 diverging into two distinct approaches. Before looking at the branching and eventual reforming of a 4th wave, let's consider a key shift in emphasis coming out of TQM in the mid-1980s.

By 1985, industrial buy in to the benefits of continuous improvement evolved to routine creation of cross-functional teams to solve complex problems. In TQM parlance these were termed Quality Improvement Teams in contrast to QC Circles. Such complex challenges go beyond purely technical issues where problem definitions are clear and solution best handled by experts. Instead, these puzzles enter the realm of adaptive problems where additional learning and collaboration are necessary. Cross-functional teams cut across organizational silos. At its core, people with different functional backgrounds bring a form of cognitive (specialization) diversity to bear on creative problem solving (Page, 2017).

In order to effectively leverage cross functional wisdom, the entire organization must subscribe to a culture of quality. So the 3rd wave, Social (QC Circle) mediator ***could*** have been expanded to a more powerful 4th wave format, Social (QC Circle + Cross-functional) component to join with Cognitive (Continuous Improvement), and Metacognitive (Deliberative Practice).

3RD WAVE DISSIPATES: WHAT'S NEXT? (1996 – PRESENT)

"Once you define your objective, you never give it up. You may find different paths to get there, but basically your objective is always there." (Sullenberger, 2012, p. 149) [Interview of Gene Kranz, former NASA Mission Control Director]

Yes, it *could* have happened that way and it can be argued that such an evolution did occur in Japan. At Toyota, for example, group development theory provided models to improve team effectiveness far beyond what was attained with 1962-1985 QC Circles. In the U.S., success of the Cross-functional teams in cost savings and quality improvements persuaded much of American management to remove support for QC Circles which were perceived as primarily *only* improving human relations and secondarily *only* moderately (slowly, steadily) improving quality. In Japan, the number of active QC Circles continued the same steady linear increase from 1962 through 1995. In the U.S., there was a sharp increase from 1980-1985 followed by an equally sharp decline from 1985-1989; then a continuing slower decline 1989 to 1995.

Let's go back to Ishikawa's Social components for *joy in the workplace* among frontline workers: (1) empowerment, (2) promotion of teamwork, (3) creation of a *secure* (literally without fear) [of failure] environment. What does empowerment mean for frontline workers *and* all those up through professionals and middle management? What activates empowerment for such individuals is: (1) Working with people who treat them with respect including autonomy for how the job is done; (2) Doing interesting or challenging work; and (3) Receiving clear goals and recognition for work well done (Schein, 2016).

People are more creative when they perceive their environment as collaborative, cooperative, and open to new ideas. This fits with Ishikawa's point (2) promotion of teamwork. Creativity is suppressed when aversion to risk taking is high which matches up with point (3) creation of a secure environment. In totality these factors explain both *stimulating greater creativity and attaining joy in the workplace*.

Membership in QC Circles was largely voluntary and the Circle remained intact project after project. Membership on Cross-functional teams was usually mandatory and the team disbanded after the project was completed. While Cognitive (Continuous Improvement) and Metacognitive (Deliberative Practice) were on the upswing from 1981 through 1989, the net Social (QC Circles + Cross-functional teams) was well in decline in the U.S. by 1989. By 1995, this Social descent was matched by leveling off of Cognitive (Continuous Improvement) and Metacognitive (Deliberative Practice) since less of either was being stimulated by shop floor activity. Again, recall the *synchronized meshed gear* and *balanced flow* analogies.

Now, let's turn to the two diverging alternatives to TQM which hopefully will re-form into a powerful sustainable 4th wave.

ALTERNATIVE 1 OF 2: TOYOTA LEAN (THE TOYOTA WAY) (1985 – PRESENT)

"[Culture is] [t]he pattern of basic assumptions that a given group has invented, discovered, or developed in learning to cope with its problems of external adaptation and internal integration, and that have worked well enough to be considered valid, and therefore, to be taught to new members as the correct way to perceive, think and feel in relation to those problems." [Edgar Schein definition of culture; identified as best match with the Toyota Way (Liker, 2004, p. 299)].

The first alternative, Lean evolved from the Toyota Production System, a 1950's child of the 2nd wave. The primary principle of this evolution to the Lean (Toyota Way) called for basing management decisions on a *long term philosophy even at the cost of short term financial gains*. The heart of the Toyota Way: [1] Foster continuous improvement and learning; [2] Teach all employees to become problem solvers; [3a] Satisfy customers while eliminating waste (any activities that do not *add value* and hence overburden people or equipment); [3b] Single piece workflow rather than a series of standalone processes; [3c] Get quality right the first time (eliminate rework); [4] Groom leaders within; and [5] Grow together with suppliers and partners for mutual benefit (Liker, 2004).

For [3] consider the educational derivative of *value added*; a buffer to rigid student progress standards. This provides a more meaningful expression of every child succeeds.

Lean is a *process*; *not a program*. All three interacting mediators on which the Toyota Production System was originally formulated (2nd wave) have been enhanced. Social ([1], [2], [3a,b&c], [4] & [5]), Cognitive ([1], [2], [3b&c], [4] & [5]) and Metacognitive ([1], [2], [3a&c], [4] & [5]) are all more vibrant. PDCA is alive and well even extending to the format for all proposals: Plan ↔ Recommendations (Cost/Benefits), Do ↔ Implementation (Plan Details), Check and Act ↔ Follow up (Expected Results--When & How they will be checked).

Social has been extended beyond Quality Circles to *all frontline workers* who are now regarded as *the primary problem solvers* even as Cross Functional teams are employed. A team (peer) leader supports each 4-8 workers; a group leader supports each 3-4 groups. In 2003, frontline workers (associates) at the Georgetown, Kentucky assembly plant made 80,000 improvement suggestions. The plant implemented 99%!

Metacognitive practice still employs PDCA and the "seven graphical tools". To these, Toyota added numerous *visual* controls so that *no problems are hidden*. This includes process mapping, visual single page reports (single sided 11x17 or 8 ½ x 11), and visual management tools placed on the plant floor so "you can manage the [plant] floor from the actual floor" (Liker, 2004, p. 167).

Toyota has achieved Ishikawa's vision, stayed true to Deming's (continuous) learning imperative, and enhanced the visual tools to problem solve. Thus appropriate labels for the Toyota Way (Lean) are: Social (Empowered secure teams), Cognitive (Continuous Improvement), and Metacognitive (Deliberative *visual* practice).

Toyota strives for zero defects as advocated by Phil Crosby but does not expect that journey to have an end date. When Toyota globalized in the 1980's, they did not perceive this as an effort to purchase offshore capacity but rather as a complex, costly, and time consuming *process* to foster the Toyota culture. What is generally perceived of Toyota is the tip of the iceberg. It's the culture below the surface that pulls together the five [5] characteristics of the Toyota Way. See Edgar Schein quote above.

ALTERNATIVE 2 OF 2: THE SIX SIGMA PHILOSOPHY (1983 – PRESENT)

"Talk to the parts; they are smarter than the engineers." (Dorian Shainin, Six Sigma guru)

The second alternative to 3rd wave TQM is Six Sigma. If Lean in simple form provides a visual understanding of process flow to eliminate "waste"; Six Sigma is a diagnostic intended to determine causes of variation to remediate "defects". With Six Sigma, the Social (e.g., QC Circles) piece is now largely voided. Temporarily, it can be filled by a motivational leader continuously driving formation of cross-functional teams to examine key defects. The team extracts then refines what was dug up into a short list of top causes (i.e., fixed nuggets of a non-renewable resource). By virtue of the Pareto 80/20 effect; if the rate of top causes can be driven down then the defect rate will be dramatically reduced.

The same motivational leader can then promote transfer of this new *cause and defect* knowledge to other facilities within the company; a leveraging bonus available to large organizations that include smaller businesses which replicate identical procedures. This external motivator might serve temporarily to fill the role of the Social gear (i.e., Social (Motivator + Cross-functional teams + Promoter). Pure Six Sigma is a mining *operation* whereas Toyota's

Lean *process* resembles drawing (renewable) compound interest (e.g., Georgetown, Kentucky fabrication plant continuous flow of "free" quality improvement ideas).

The Cognitive (Continuous Improvement) piece is replaced by Cognitive (Discrete Breakthroughs). The Metacognitive (Deliberative Practice) built upon the "seven graphical techniques" is replaced (or enhanced) by a toolset adding monitoring, searching, validating, and sorting of causes. The cause sorting allows full factorial Design of Experiments to reveal a central cause and interactions.

The noted compatibility of fit between the *6 step method and PDCA* matches a comparable fit between the *McMaster 5 point strategy and DMAIC*. These are two fundamentally distinct improvement philosophies [steady *continuous improvement* vs. stop and start *discrete breakthroughs*].

MOTOROLA SIX SIGMA: 4TH WAVE FAILURE (1983 – PRESENT)

"Do not fear mistakes. Wisdom is often born of such mistakes." (Paul Galvin (1895-1959))
"When the well is dry, we know the value of water." (Ben Franklin)

Motorola was a multinational telecommunications company founded in 1928 by brothers Paul and Joseph Galvin in Chicago, Illinois. State of the art mobile radios, microprocessors, NASA transceivers, and the first cell phone represent highly innovative products developed by Motorola 1930s through early 1990s. The company originated Six Sigma in 1983, formally launched it in 1986, and made it their sole and singular quality answer in 1989; the same year they disclosed its contents. Motorola brought in the brilliant reliability expert, Dorian Shainin to spearhead the effort. Originally, the overarching method selected in place of the PDCA cycle was a 4 step plan (MAIC); however, prior to the 1989 disclosure; IBM acting as strategic partner to Motorola recommended a lead in step and so the 5 step method became DMAIC:

(1) Define [Id objective, business case, create project charter/scope/milestones]
(2) Measure [Select feature(s)/Process map/Validate *measure* systems/Collect data]
(3) Analyze [Estimate process capability/Benchmark perform metrics/ID success]
(4) Improve [Use variation drivers/Find & Test solutions/Analyze cost/benefit]
(5) Control [Implement new process/Change systems & structures/Finalize savings]

The Six Sigma method contains two phases: MA (diagnosis), and IC (optimization). Define clarifies this is a top down procedure; one aimed not at continuous improvement but at quantum leap breakthroughs. At Motorola, tools were all from Shainin: 15 charting, monitoring, searching, validating, and comparison techniques developed 1945−1977.

The generic "seven graphical techniques" of 3rd wave TQM were derided as kindergarten tools even though equivalent Shainin instruments are essential features. For example, the Pareto/Lorenz characteristic curve is critical to Shainin/Motorola Six Sigma. Use of standard statistical techniques; e.g., ANOVA and Regression were similarly eschewed in favor of equivalents. While working with Motorola (1986−1988), Shainin developed a bridge tool from diagnosis to optimization to hone in on the short list of suspect causes (Search for Red X). The results were fed into Fisher's classic full factorial method to disclose the primary cause (Red X) and interactions with secondary & tertiary causes (Pink X and Pale Pink X) on defect (Green Y) reduction. This combination provided a practical method to apply Design of Experiments.

From 1981−1986, Motorola by employing 3rd wave TQM saw their quality improve 10-fold over the 5 year period with an average yearly productivity gain of 7.5%. Their Japanese competitors steeped in 2nd wave quality experience were doing a tick better with average yearly productivity gains of 8%. Motorola was concerned that their competition was now approaching 4 sigma on critical production characteristics (roughly 6,200 defects per million). By focusing on a six sigma mission (3.4 defects per million), Motorola felt they could leap over any competitor. From 1986 to 1988 and again from 1988 to 1990; they saw 9-fold quality improvements (in each short 2 year period). Motorola would attain 4.3 sigma on their critical production characteristics in 1999 (3,000 parts per million). The future looked bright.

But clouds were already on the horizon in the late 1990s. By this time, Motorola owned many of the critical patents necessary for emerging digital platforms. So while the general public in the U.S. loved the Motorola analog phone, Motorola was reaping large profits based on royalties for digital networks being set up in Europe and Asia yet leadership could not see the urgency in releasing a digital product. A new U.S. competitor, Qualcomm launched in 1985 slanted their introductions into digital. By 1999, the vast majority of hundreds of Motorola's network engineers were using Qualcomm digital phones (Arena, 2018).

So while Motorola executives were moving their culture toward "talking to the parts"; communications with their design engineers was suffering. Motorola was now a dozen years along their Six Sigma journey.

From 1959–1986, Bob Galvin, son of co-founder Paul Galvin was CEO; continuing as Board Chairman through 1992. An in-house 3 member office of the CEO operated from 1987–1996 until Bob Galvin's son, Chris Galvin formally assumed the reins (1997–2003). The first nonfamily CEO, Edward Zander from Sun Microsystems ran Motorola (2004–2008). Motorola's zenith occurred around 2006; 2 years after introduction of their Razr cellphone but then in 2008 a significant decline began.

Some analysts claim the downturn of fortunes was due to the iPhone introduction in 2008; others to competition from companies like Nokia and slow release of a follow-up product to the Razr under leadership of Edward Zander. Author would like the reader to consider *lack of balanced flow* and *voiding of the Social support gear* under the Six Sigma implementation, the *change in leadership*, and an unintended consequence; Six Sigma philosophy *stifling creativity* necessary for new product innovation. This creative aspect is inherent in Experiential Divergent Methods and missing in total reliance on Analytical Convergent Methods.

GE SIX SIGMA: 4TH WAVE ROCKET RISE THEN CRASH (1995 – PRESENT)

"I just want to say one word to you … just one word. Plastics" (The Graduate, 1967)
"Oh, it's fine to be a genius of course But keep that old horse Before the cart First you've got to have heart" (Damn Yankees, 1955)

The Six Sigma program is often described as "originated at Motorola but perfected at General Electric (GE)". Jack Welch was CEO of GE (1981-2000) followed by: Jeff Immelt (2000-2017), Interim CEO John Flannery (2017-2018), and H. Lawrence Culp (2018-Present). In 1960, Jack Welch came to work at a small R&D branch of GE, GE Plastics. This was after earning B.S., M.S., and Ph.D. degrees in chemical engineering. In 1968, Welch became the youngest general manager at GE. For, at age 33, Welch was named General Manager of GE Plastics to oversee development of LEXAN and NORYL plastic products.

Between 1981 and 1985, Welch as CEO reconfigured GE by divesting about 50% of the manufacturing businesses and investing in significantly more service (particularly financial and credit) and somewhat more technology based (particularly medical care) businesses. A GE bureaucracy delayering eliminated 3 levels of management (9 layers to 6). During these reorganizational years, GE productivity was locked between 1% and 3%. Again, GE saw the same trend as Motorola; GE's Japanese competitors were boosting productivity by 8% per year.

GE began their quality journey late. From 1986 to 1989 they employed a standard 3rd wave form of TQM. In October 1988, GE launched Work-Out, an ambitious 10 year educational program intended to alter employees' behavior and instill an enduring shared culture. Initial goals were for greater front line worker input, continuous improvement, and deliberative practice built around the "seven graphical techniques". In this phase, GE annual productivity improved into the 4% to 6% range.

From 1989 to early 1995, GE was evolving 3rd wave TQM in a similar fashion to the Toyota natural organic continuous improvement process. Nonproductive tasks were identified and eliminated to allow more creative work environments. Input from all levels of employees was solicited on better ways to do their jobs. Empowerment of all workers including front line workers was the goal. Worldwide best practices were also pursued.

Then in late 1995, Jack Welch became enamored by the Six Sigma philosophy. Welch often cited the writing of his doctoral thesis (*Role of Condensation in Nuclear Steam-Supply Systems*) as basic to understand his ability to take on a complex multi-factor problem and after "going down all the blind alleys … until I got it to where it was simple … simple … the most elegant thing one can be" (Tiechy & Sherman, 1993, p. 48).

GE, like Toyota routinely employed process mapping but once Six Sigma was institutionalized, simple process maps came to routinely fill entire office walls as each and every nuanced step was documented and assigned elapsed and total completion times. The flavor of Six Sigma promulgated by GE was more flexible than Motorola's Six Sigma. GE did not throw out the "seven graphical techniques". Other than Shainin's "Search for Red X"; standard tools were the rule. Techniques like Brainstorming, ANOVA, and Regression were on the table. GE General Managers (GMs mainly Ivy League business analysts) moved freely among divisions. The belief was that number crunching analytical expertise trumped product process knowledge.

When Jack Welch retired from GE in 2000, he was convinced that he had created a new and enduring GE culture. Welch claimed his legacy should be judged not in terms of what he accomplished in his 20 years as CEO (1981-2000) but by what GE looked like at the end of the next 20 years (2020). His hand-picked business analyst successor, Jeff Immelt, CEO (2000-2017) worked closely with Welch while GM of GE Medical Systems (GEMS). Welch routinely leveraged Six Sigma breakthroughs by stirring communications and sharing of common defect reduction among GE Financial Services, GE Plastics, and GE Medical Systems. Immelt took GE back into more manufacturing while divesting businesses in Financial Services and Plastics.

The September 11, 2001 trade center terrorist attack (weeks after Immelt took charge) and the 2008 recession are often cited as reasons for GE's general decline. Author would like the reader to consider *lack of the Six Sigma Social support gear*, the *change in leadership*, and *increasing difficulty to mine, refine, duplicate, and replicate breakthroughs*.

4TH WAVE CONTENDER, USAF: A LEAN SIX SIGMA HYBRID (1996 – PRESENT)

"We must fundamentally change the culture of our Air Force so that all Airmen understand their individual role in improving their daily processes and eliminating things that don't add value to the mission … The Lean concept includes two predominant process attributes: Do it right the first time. Stop doing non mission-critical tasks." (Col. Sheri Andino)

In 1996, the United States Air Force (USAF) began exploration of a "new culture" that while similar to the 1981–1994 3rd wave TQM quality movement would focus upon impacting mission performance. This time; based on lessons learned from the 1995 aftermath of the earlier effort, the initiative would be so tightly woven into the USAF culture and so clearly understood up and down the ranks that it would be sustainable.

By 2009, after 7 years of experimentation (2001–2008), the concept was crystallized into a shared vision. Toyota, as the largest and most successful business in the world would serve as primary model for the largest and most successful Air Force in the world. An 8 step method while heavily slanted toward PDCA would incorporate Six Sigma features:

(1)	Define:	Clarify and validate the problem		(Plan)
(2)	Observe:	Break problem down; Identify performance gaps		(Plan)
(3)	Define Goals:	Set improvement target	(Simplified Six Sigma Analyze)	
(4)	Orient:	Determine root cause	(Six Sigma Improve)	
(5)	Action Plan:	Develop corrective action	(Transition)	(Do)
(6)	Implement:	Implement corrective action		(Do)
(7)	Evaluate:	Confirm results & processes		(Check)
(8)	Standardize:	If it works a new Standard Operating Procedure is written,		(Act)
		If it fails to work then abandon and recycle.		(Act)

With a backdrop of the *synchronized meshed gear and balanced flow analogies* in mind; let's dig into how the Toyota Way was to be modified to fit into the USAF. Continuous improvement, focus on process, and flexibility were natural matches. Although, where flexibility at Toyota (and other Japanese auto manufacturers) meant quick changeover responsive to customers' changing needs; the flexibility required by the USAF need was much more moment to moment. *Elimination of waste was redirected from manufacturing process needs to critical mission needs*. Whereas Toyota sought *quality & reliability* in an efficient *cost effective* and *visually clean manufacturing environment*; the USAF equivalent was *responsiveness & dependability* in an *air dominant and visually supportive air domain*. The carryover to reporting: Clear and concise communication (preference single sided one page 8 ½ x 11 format).

The Toyota *focus on frontline shop floor associates* relative to *manufacturing prowess* supported by the rest of the workforce would be translated to a *focus on airmen* relative to their *mission performance* supported by all other service personnel (regardless of rank). The airmen needed to be creative when literally under the gun by being able to focus on their work as it unfolded in real time. Breaking this down into a *3 gear synchronized mesh balance flow model*:

1) Social (Empowered secure teams): The goal was to move to self-managed work teams. Commanders would then spend more time on strategies and improvements including extending improvement ideas to partners.
2) Cognitive (Continuous Improvement): The commitment is that all airmen will develop into keener problem solvers just as frontline workers at Toyota have developed their problem solving skills; by team (peer) learning. Where 1981–1984 TQM attempted to look at continuous improvement of *all existing processes*; the new commitment is to *examine processes which are mission critical*.
3) Metacognitive (Deliberative *visual* practice): The USAF looks to commit to modifying their strategic practices and tools to benefit workflow.

Based on the discussion of pure Six Sigma at Motorola and GE, the author has a concern that employing useful Analytical Convergent Method tools could drift into decoupling the Social gear in opposition to *balanced flow* and *synchronized mesh*. Leadership must be vigilant to avoid slippage inherent in moving from Cognitive Continuous Improvement to Breakthrough (quantum leaps) caused by devaluing the Social gear. Since the heart and soul of both Social and Cognitive efforts revolves around execution of a problem solving method from the Meta-cognitive gear; this is a particular point of vulnerability. Safeguards to keep the Social gear intact and the Cognitive gear grounded in Continuous Improvement will be dependent on keeping the 8 step method responsive to this long term vision.

One possibility comes to mind for advancing the urgency inherent with the Experiential Divergent Cycle included as part of the 8 step method. That is for (1)→(2) and (5)→(8) and back to successive cycles at (1) not to be bogged down in steps (3) and (4) (Analytical Convergence). Imagine a 12 member team coming through step (3) and just beginning step (4). At this point the team would reach consensus as to 3 likely causes from among all those so far identified.

Direct a group of 3 to peel off and continue the experiential loop at (5). When the 3 member group completes the remainder of the cycle and rejoins the main team; they can discuss lessons learned experientially. Perhaps the decision is that indeed one of the factors still looks like promising but no go on the other two. The group of 3 then is tasked with exploring two more likely candidates and interaction with the holdover factor. They proceed on a 2nd cycle. By then, the root cause analysis should be well underway but now backed up with experience necessary to complete the final loop.

Essentially, this would reorient the 8 step method into two loops; *one experiential* and *one analytical*. If the same 12 member team approaches a new problem; a different group of 3 would peel off granting airmen cross training in both *Experiential Divergent* and *Analytical Convergent Methods*.

SPECIAL CASE OF DIVERSITY

"It is hardly possible to overrate the value … of placing human beings in contact with persons dissimilar to themselves, and with modes of thought and action unlike those with which they are familiar. … Such communication has always been…one of the primary sources of progress." (John Stuart Mill, 1848)

There are three forms of diversity: (1) identity diversity (race, gender, age, etc.), (2) conative diversity, and (3) cognitive (specialization) diversity.

The most vulnerable identity group within STEMM was/is African American Males. In fall 2008, % African American Males in the School of Technology = 6.61%. From fall 2009 through fall 2016 (height of ENTC 1500 offerings), the average percentage = 11.01%. In the 4 academic years, 2012 through 2016 (height of STEM 1513 offerings), the average % of African American Males = 3.39%. For academic years 2017, 2018 & 2019, the percentage of African American Males averaged 2.48%. Whereas, all other outcomes (CARE) were fit as linear combinations of predictor variables, diversity was a power fit.

$\text{Identity Diversity}_{ET}(I) = 3.764 \cdot [\text{SOCL}(I)]^{0.2385}$

$\text{Identity Diversity}_{STEMM}(I) \approx (3.764/F) \cdot [\text{SOCL}(I)]^{0.2385/F}$ where $F = 0.35/0.67 = 0.5224$

STB CAUSAL MODEL VALIDITY

"The only relevant test of the validity of a hypothesis is comparison of prediction with experience." (Milton Friedman)

Curve fits of program outputs for engineering technology students produced equation coefficients used to predict outcome changes for students in other STEMM disciplines. Results are detailed on Figure 3 at end of study. Actual detailed results are available on Achievement, Enrollment and Diversity. These form the basis for validating the causal model:

(1) Achievement: Raw RDD results at point of discontinuity (ACT math = 21.5) provided consistent outcomes across interventions: 32 – 33% (+ 0.6 GPA) in Calculus and for 3 of the 4 targeted core course sequences (engineering technology, physics, and biology); a spread of just 19 – 23% (+ 0.4 GPA).
(2) Enrollment: The predicted change in STEMM enrollment due to STEM 1513 was 14.9% to which the COFSP Offset (+3.2%) was added; 14.9% + 3.2% = 18.1%. This compares favorably with the actual change in STEMM enrollment obtained through annual 14th day fall enrollment figures of 18.9% ($\Delta = -0.8\%$).
(3) Diversity: The predicted change in STEMM identity diversity due to STEM 1513 was 0.85%. This again compares favorably with the actual change obtained from fall annual reports of 0.91% ($\Delta = -0.06\%$).

PREDICTION STEP 1: CORRECT RAW DATA FOR COFSP EFFECT

"Never tell people how to do things. Tell them what to do and they will surprise you with their ingenuity." (Gen. George S. Patton)

Running in parallel with the two interventions [ENTC 1500 (2008-2016) and STEM 1513 (2012-2016)] was a program specifically limited to STEMM control group members--the Choose Ohio First Scholarship Program (COFSP) (2008-Present). COFSP was treated as a steady state factor (2011-Present). COFSP provides 4 facets improving STEMM outcomes for students (traditional only); none of whom were treated by ENTC 1500 or STEM 1513:

1) No cost 4 week on-campus Summer Intermediate Algebra (Algebra 2) to Pre-Calculus Bridge Program for targeted urban high poverty school district students who wish to pursue a STEMM major in college; tangible long lasting math skill effects evidenced.
2) A high value scholarship program for STEMM majors with priority on eligible students who previously participated in Summer Bridge.
3) Scholarship awardees are supported by a Coordinator of STEM Outreach including providing tutoring, if necessary. All awardees attend monthly cohort meetings where 20 groups of 4 to 6 students each with a faculty mentor develop a yearly project presented on campus and at a regional juried and competitive student research conference. Placement of junior and senior students into co-ops and internships is extremely high.
4) The program complies with a mission of math enrichment; i.e., activities meant to broaden educational lives of group members. Implemented by teachers and mentors experienced in working with "gifted" students; enrichment programs overall carry an effect size, $d = 0.39$. Enrichment is stronger in math ($d = 1.10$) and in sciences ($d = 1.23$) than in reading ($d = 0.59$) or social studies ($d = 0.23$). (Hattie, 2009).

COFSP adds 25 traditional freshmen each year to maintain an undergraduate cohort of 100 students. The distribution across majors is non-uniform. If uniform then the contribution of COFSP relative to retention and enrollment could be pegged at 3.8% across the board. However; the actual distribution by major (using fall 2012 data) varies widely: 55 Engineering (55/469 = 11.7%), 3 Physics (3/37 = 8.1%), 8 Chemistry (8/209 = 3.8%), 21 Biology (21/603 = 3.5%), 3 Geology/Environmental Studies (3/106 = 2.8%), 6 Computer Science/IT (6/524 = 1.1%), 1 Mathematics (1/94 = 1.1%), and 3 Engineering Technology (3/307 = 1.0%).

So, COFSP student involvement (fall 2012) represented 3/(0.5 x 307) = 2.0% of untreated control group engineering technology students and 97/((1 − 0.209) x 2342) = 5.2% of untreated students in other STEMM disciplines (Δ = 3.2%).

Y(0,1) is a shorthand for the ordered pair of untreated and treated (by STB) groups. The boundary conditions for the first value of the pair for all 3 areas of mediation (Social, Cognitive, and Metacognitive) as well as Resilience and net change in Achievement were corrected for the COFSP effect as indicated below. The COFSP offset (+3.2%) plays an essential role in predicting Retention & Enrollment for the students treated by STEM 1513 (see Figure 3).

RESULTS OF STEP 1: COFSP CORRECTIONS

ENTC: SOCL(0,1) = (10,100)⇨(11.8,100); COG(0,1) = (50,100)⇨(51,100); MCOG(0,1) = (10,100)⇨(11.8,100); RESIL(0,1) = (3,30)⇨(3.54,30); ACHV(0,1) = (0,25.3)⇨(0,25.8)

STEM: SOCL(0,1) = (5,100)⇨(9.94,100); COG(0,1) = (50,100)⇨(52.6,100); MCOG(0,1) = (0, 100)⇨(5.2,100); RESIL(0,1) = (0,30)⇨(1.56,30); ACHV(0,1) = (0,25.3)⇨(0,26.6)

PREDICTION STEP 2: CORRECT DATA FOR PARTICIPATION RATES

"Omne trium Perfectum"−An ancient Latin expression translated as "All things Divine come in threes." Are triads (1) a spiritual manifestation, (2) the simplest combination to form a pattern, or (3) just another expression of the Pareto/Lorentz Principle?

ENTC 1500 was applied to 50% of students; STEM 1513 to 20.9%; in each case the target was students in greatest need. If key predictor variables for the CARED outcomes have been properly identified and quantified then per Pareto/Lorentz curve; their effects on the overall engineering technology program will be 90%; 80% (80/20 rule) on the rest of STEMM programs. Therefore, Social, Cognitive & Metacognitive mediators as well as Resilience, and Achievement were multiplied by 0.90 for engineering technology; by 0.80 for other STEMM disciplines. Pareto factor multipliers applied to Diversity were 0.67 and 0.35 respectively.

RESULTS OF STEP 2: PARETO WEIGHING CORRECTIONS

ENTC: SOCL(0,1) = (11.8,100)⇨(10.6,90); COG(0,1) = (51,100)⇨(45.9,90); MCOG(0,1) = (11.8,100)⇨(10.6,90); RESIL(0,1) = (3.54,30)⇨(3.19,27); ACHV(0,1) = (0,25.8)⇨(0,23.2)

STEM: SOCL(0,1) = (9.94,100)⇨(7.95,80); COG(0,1) = (52.6,100)⇨(42.1,80); MCOG(0,1) = (5.2,100)⇨(4.16,80); RESIL(0,1) = (1.56,30)⇨(1.25,24); ACHV(0,1) = (0,26.6)⇨(0,21.3)

LIMITATIONS

Serenity Prayer: "God grant me the serenity to accept the things I cannot change, courage to change the things I can, and wisdom to know the difference." (Reinhold Niebuhr, 1933; modified by AA cofounder, William G. Wilson, 1941)

The achievement effect of the generic version of STEM 1513 produced no long term gain in follow-up Chemistry Achievement even as taught by an outstanding adjunct chemistry teacher. The generic version focused on the numeracy realm which served admirably for Calculus, Physics and Biology. A modest + 8.8% (+ 0.162 GPA) gain was obtained in follow-up Chemistry sequence for a subgroup of students exposed to a more intense literacy component (i.e., practice on written [and oft re-written] *analyses*) of primarily *process* based lab results.

As Analysis of Results is based on an Analytical Convergent Method this appears to be the answer. That is, ***adoption of method(s) well-suited to types of problems to be solved***. For example, the McMaster 5 point strategy would take precedence over Experiential Divergent Methods like the six step method. This same approach would likely improve performance in business analytics coursework. There are also common tools successful in bridging the arts and sciences while promoting each. These tools include: analogies, narratives, collaborations, and efforts aimed at improving faculties in perceptions of motion, emotion and natural patterns. Such skills can be molded into valuable frameworks by use of drawings and sketches to spur thinking; mindful experiments to evaluate concepts by visualizing them. (Isaacson, 2017)

SUGGESTIONS FOR FUTURE STUDIES

"True quality comes from a philosophy built around creating a culture." (Phil Crosby)

(1) Study the Choose Ohio First Scholarship Program (COFSP): A quantitative or mixed method study could be undertaken to accurately determine outcome effects; focus to contrast benefits for summer bridge members and non-members.
(2) Develop and Study more analytically based customized variations of STB. What effect would linking such a modified STB have on outcomes targeted at chemistry students? At chemical engineers? At business students? Variants in the arts, humanities, and human services?
(3) Study Expansion of STB Teaching & Learning across Grades 7 through 12: A 2014 multi-county professional development committee (grades 7-9 math and science teachers) chaired by the author suggested diverging priorities toward learning/applying an STB like approach. A needs assessment disclosed importance of producing an expandable resource portfolio of student experiential labs/activities developed by teacher participants. Especially significant is that these labs and activities match state standards. Branching intentions by those interested: (1) solely in professional development, and (2) receiving credit toward a Master's in Education degree at a reasonable cost.
(4) Explore effect of STB on capstone performance.
(5) Study handoff of STB to Inquiry Based Teaching and Learning.
(6) Develop a Business Case Study to examine the business effect of CEOs coming from the GE Six Sigma culture (e.g., Robert Louis Nardelli and James McNerney).

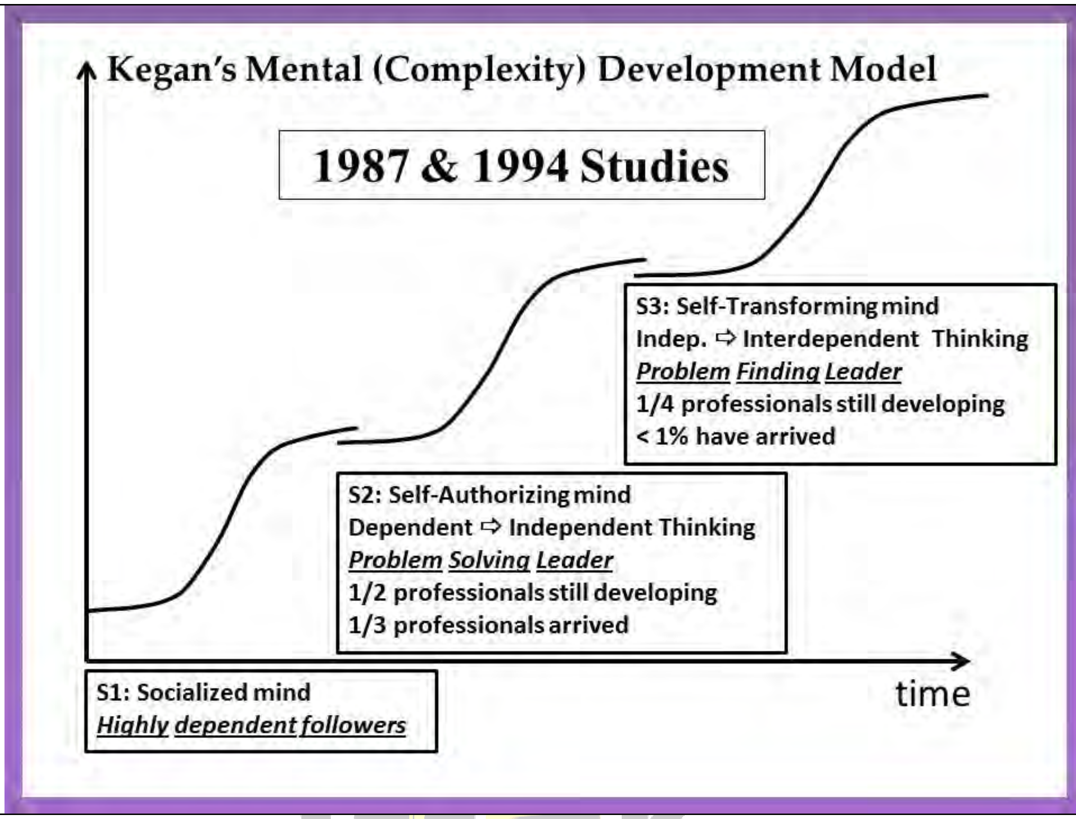

Figure 1: Kegan's Developmental Model

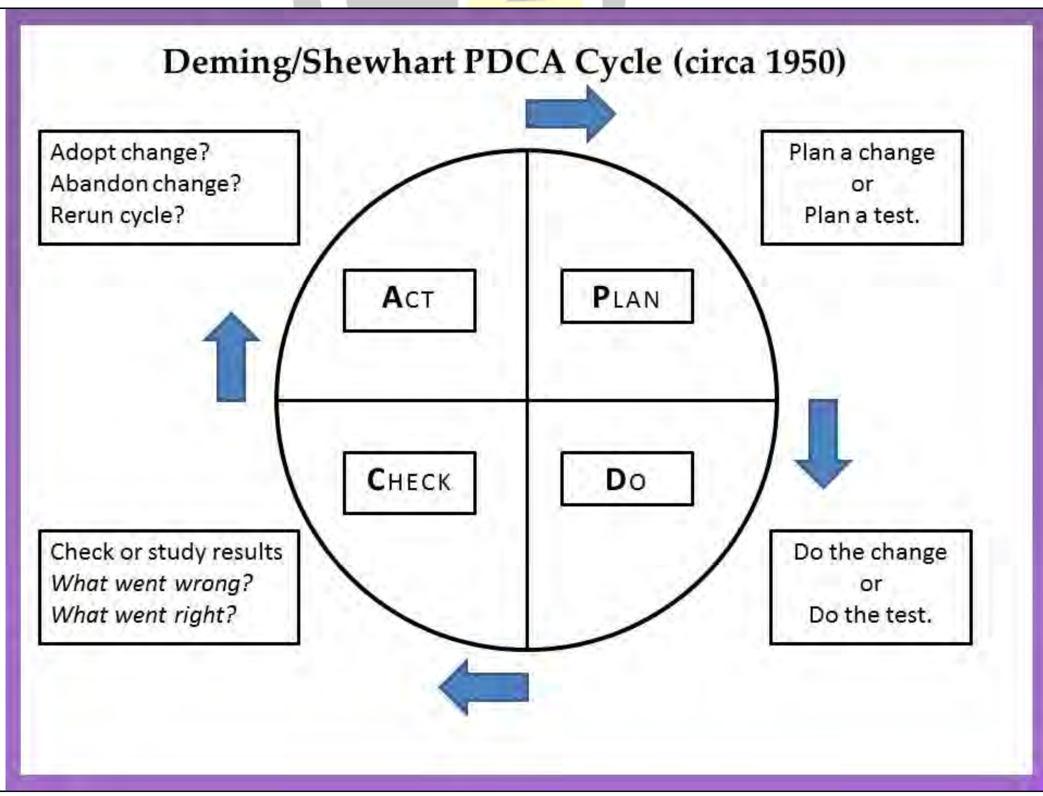

Figure 2: Deming/Shewhart PDCA Cycle

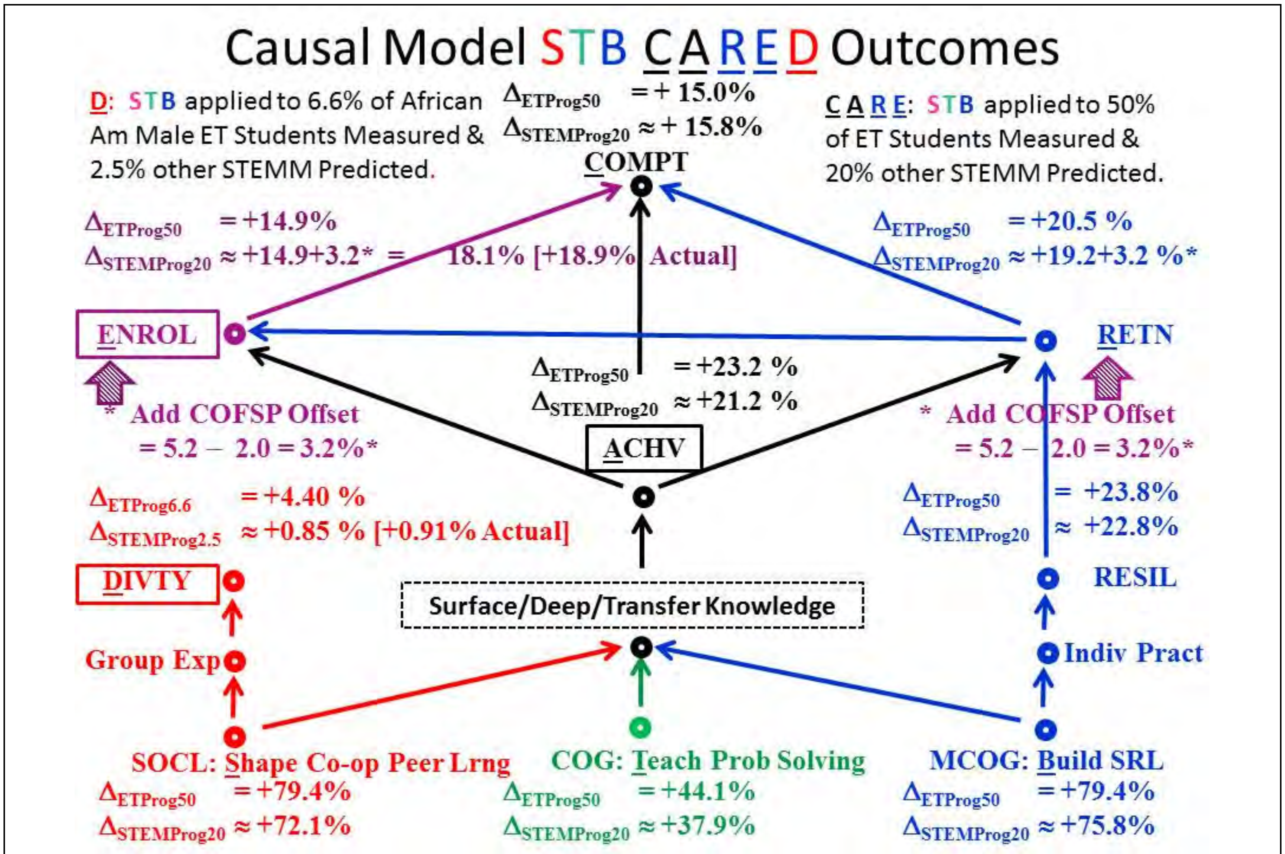

Figure 3: Causal Diagram for **STB** (STEMM College students)

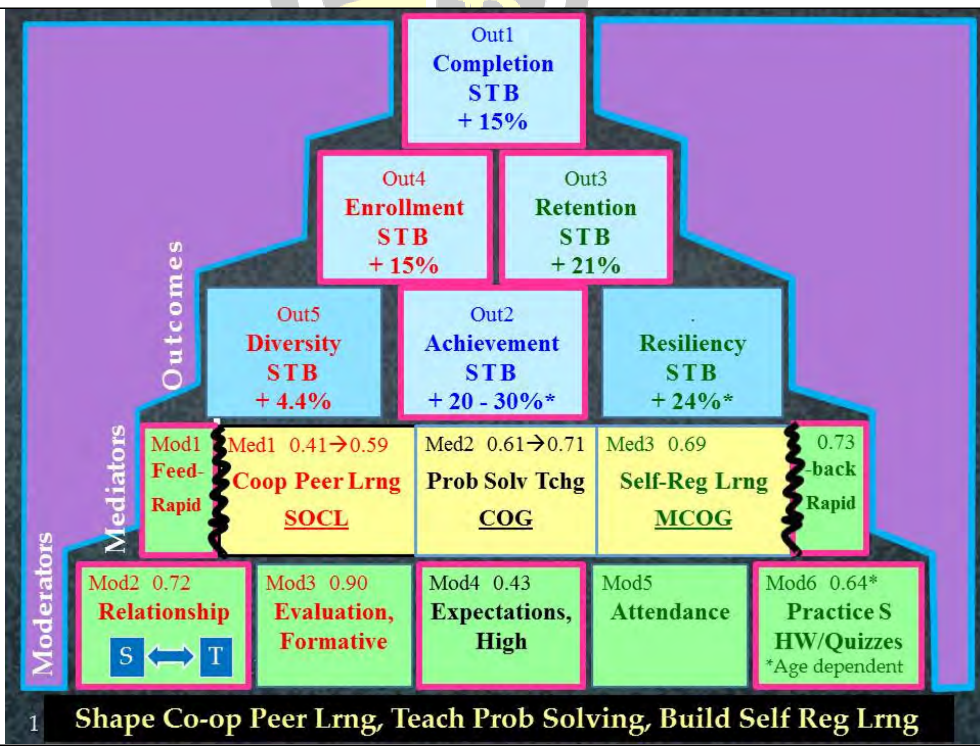

Figure 4: **STB** Pyramid (Wooden & Jamison, p. 2) Model of Teaching & Learning

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